LOWEST COST BUILDING TECHNOLOGY SELECTION FOR ENERGY EFFICIENT DESIGN

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by

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LOWEST COST BUILDING TECHNOLOGY SELECTION FOR ENERGY EFFICIENT DESIGN

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ACKNOWLEDGEMENTS

I wish to thank Godfried Augenbroe, for his insightful words and direction on this project and others. I would also like to thank Matthias H.Y. Tan for his help with MATLAB and his brilliant insights into the process of optimization as well as Sang Hoon Lee for his technical support of EPSCT.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACH	Air Changes per Hour
COP	Coefficient of Performance
EUI	Energy Use Index
HVAC	Heating, Ventilation and Air-Conditioning
kWh	Kilo-Watt-Hour
SIP	Structurally Insulated Panel

SUMMARY

The thesis project explores the use of an optimization methodology for selecting the lowest monetary cost combinations of technologies to meet a set operational energy efficiency targets for buildings. The optimization approach, which is operated on a normative energy model, is compared with existing prescriptive methodologies for selecting technology combinations and a metric is developed for ranking their effectiveness; the E/C Ratio. The energy savings/ cost ratio is also the objective function that the optimization algorithm is set to maximize. The optimization routine is coded in to a custom MATLAB script and is used in two case studies to optimize a proto-typical Korean apartment and office building. The optimization methodology finds technology combinations that are much more cost effective than the prescriptive methodology at meeting an energy savings target and can generically be applied to other buildings given a palette of technology alternatives and the corresponding cost data.

CHAPTER 1

INTRODUCTION

The manufacturers of building materials, systems, and technologies continue to create larger palettes of products and levels of accomplishment within them. Each instance of a technology or systems is considered to have effectiveness in its own right which can be ranked against others in its class. For example, the level of accomplishment of HVAC systems, boilers, and heat recovery units would be their macro system efficiency which can be ranked in order by each manufacturer. The level of accomplishment is an important distinction from the performance of the whole building, although each technology can be ranked by its level of accomplishment its actual performance can only be measured as part of the whole building system.

This process of expanding options exponentially increases the already broad spectrum of available design alternatives. The vast array of alternatives available for buildings can be seen as a discrete combinatorial space made up of all the possible combinations of levels of accomplishment in each technology category. Surveying this combinatorial design space reveals a dizzying number of possible technology combinations. For example, given 16 technology types with between 2 to 7 levels of accomplishment each, there exist more than 170 million unique combinations. The motivation to explore this combinatorial space of technology options is to develop rigorous methodology for finding low cost solutions for meeting the energy saving goals required by international energy codes which enforce better performing buildings.

The American Institute of Architects created the 2030 challenge with the goal that all new buildings designed in the year 2030 and after will use net-zero site energy. The Korean government is currently pursuing even more aggressive legislation that will require all new buildings to use net-zero energy 2025. In this instance, the net-zero building uses zero energy at the site meaning the energy produced at the site must meet or exceed the energy consumed by the building.

The pathway towards that goal requires an incremental and affordable energy saving strategy. Many prescriptive building codes and guidelines such as LEED and ASHRAE Advanced Energy Design Guide in the US and Passivhaus in UK present a step by step method to reduce building energy use. These guides do not necessarily result in the selection of financially viable technology combinations and so not provide a cost-effective path for owners to meet energy saving goals. To meet energy reduction targets an optimization process is developed as the most efficient way to find sets of technology mixes that meet the energy saving constraints but do so at minimal cost.

Typical Buildings Selected for Case Study:

Two buildings have been selected to study the application of both prescriptive design methodologies and an optimization process to compare each procedure's effectiveness at meeting an energy saving constraints at the lowest cost. A 10 story 8,467 square meter office and a 15 story 60 unit 6,028 square meter apartment building have been selected as representations of the proto-typical Korean buildings. The buildings are situated in the urban capital city of Seoul, Korea. The weather data used in the study is from the Incheon airport at latitude 37.48 degrees and longitude 126.55 degrees, which has a similar coastal climate to the city of Baltimore in the United State at latitude 39.28 degrees. For the purpose of this study the ASHRAE design guidelines for Baltimore in climate zone 4 are applied to the case study buildings.

The two proto-typical buildings, apartment and office, are modeled with a normative energy modeling tool which calculates the yearly energy use intensity (EUI) of each building with the given climate data. The following virtual experiments in energy modeling explore the application of prescriptive design methodologies against an optimization framework to meet the energy reduction targets which are externally imposed by international energy codes and internally required by an increasing number of owners. The two methodologies are first compared in their ability to reach the desired energy targets, 30% and 50% energy savings, as well as the monetary cost as a consequence of applying each strategy. A single metric is developed for evaluating each strategy's efficiency for saving energy at minimal monetary cost; The E/C Ratio. The goal of this study is to find an optimization methodology that maximize the Energy Savings/Cost Ratio, and produces a unique combination of technologies and their corresponding levels of accomplishment for each building. The optimization methodology is also quantitatively ranked with the E/C Ratio against the prescriptive applications of ASHRAE Energy Design Guide and Passivhaus.

CHAPTER 2

MODELING

This study uses a normative energy calculation approach which is defined by ISO 13970 and CEN 15603. The ISO-CEN whole building energy modeling approach has been coded into an excel calculator that solves algebraic heat balance equations with average monthly weather data. The calculator's output is an energy use intensity, i.e. the yearly energy used per unit floor area in kilo-watt hours per square meter per year ($kWh/m^2/year$) is used in benchmarking the building's performance rating as an EPC or energy performance coefficient. This approach has been proven superior to the dynamic simulation method specified by ASHRAE 90.1, Appendix G, which is required by the LEED rating system for benchmarking building performance. The normative model is composed of a set of algebraic heat balance equations and is much simpler than the corresponding dynamic simulation model which solves a full set of partial differential equations and requires exponentially more computation time. The normative modeling methodology and has been shown to lead to the same ranking of alternatives as a much more complex model and thus reach the same decision about selecting energy conservation measures. (Augenbroe 2005)

The Energy Performance Standard Calculation Toolkit (EPSCT) is a whole building energy modeling approach which is used to analyze the combinatorial space of technology parameters in the proto-typical buildings. The optimization process must be operated on a whole building energy model because sub-optimizing only a subset of technology parameters will not lead to an optimized building because the performance of each technology cannot judged on their own but rather as part of the whole building system. (Augenbroe 2011) asserts that there is simply no method that attempts to sub-optimize the building or a building system by simply selecting the components with the highest achievement, rather the whole building's performance must be evaluated as function of all parameters. Since the EPSCT methodology is also normatively defined it removes the bias created by the modeler in the production of a complex dynamic simulation. Furthermore, as the goal is to select technologies based on total yearly energy consumption, the normative calculation has been proven to be accurate enough for that purpose.

Prescriptive energy codes and guidelines bias the technologies the design team selects because this reductive method only lists a small segment of the technologies available at the time of publishing and is influenced by the authors' preferences. A performative indicator like energy use intensity actually measures the whole building energy performance and can account for the complexities of interactions between different technologies. A similar performance based code would also allow for compliance through innovation and does not restrict the path selected to reach the performance requirement. For example, if a design space of 16 parameters has 170 million possible combinations, the prescriptive compliant building is just one data point in a vast array of possible solutions that meet an energy reduction target and most likely is not the monetary cost-optimal one. If the possible combinations are seen as a potential population of typical buildings then a Monte-Carlo random sampling method can be used to enumerate some of this population. Figure 2.1 shows an example population of Korean office buildings as a probability density function from 10,000 random sample points. In this population the mean building has an EUI of 135 kWh/m^2/year, of which there are almost 280 instances. The optimization methodology is on that searches the combinatorial space, or potential population of buildings for the one set of alternatives that meets the energy saving objective at the lowest monetary cost.

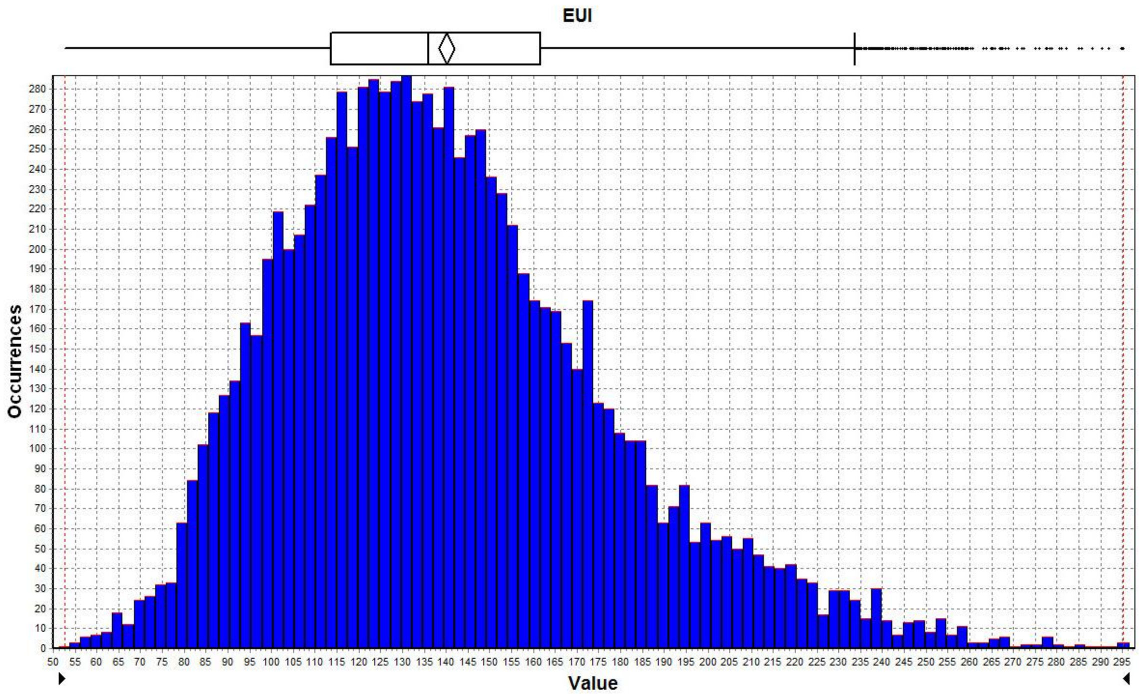

Figure 2.1: Population of Potential Buildings

Baseline Buildings:

The baseline building performance for the apartment and office building are calculated by applying the prescriptive Korean building code to each building which governs the maximum allowable conductivity values for the building's envelope. The Korean building code varies for each of its three regions; Central, Southern and Jeju Island. Seoul is in the Central Region of Korea so the building codes that apply there are used as the definitions of the baseline buildings envelope properties. (Figure A.1) The occupancy schedule for the office building is defined as 100% occupancy for weekdays Monday - Friday, 9:00am - 6:00pm, with no other occupied times. The occupancy schedule for the apartment building is interpolated at hourly points from a continuous model. (Richardson 2008) (Figure A.2) The baseline office and apartment building's yearly energy use intensity as calculated with the normative Excel tool is 320 and 346 kWh/m^2/year respectively. The heating and cooling demand, before efficiencies of mechanical equipment is considered, for the baseline office building is 66 and 49 kWh/m^2/year respectively while for the demands are baseline apartment building are 69 and 35 kWh/m^2/year which show that the Central Region of Korea is a heating dominated climate zone.

The monetary cost function this study aims to minimize is a linear sum of 16 technology parameters at their corresponding levels achievement. The premium monetary costs are defined as the cost of any parameters' level of achievement cost minus baseline cost then the all the parameters in technology category are summed to calculate total premium cost.

For example, any technology that is not included in the baseline building but is added later as in the case of renewables and heat recovery, the premium is cost is just the total cost of the technology since the baseline cost of that parameter is zero or null. Since the cost of each parameter is subtracted from the baseline cost; the premium cost of any two baseline buildings equals zero. The cost function can be written as $C(\boldsymbol{x}) = \sum_{i=1}^{p} A_i(x_i)$, where $x_i \in \{0,1,\dots,n_i\}$, and for each baseline building each $x_i = 0$ therefore $C(\boldsymbol{x}) = 0$. This method of costing removes the time sensitivity of technology cost and excludes Net Present Value or return on investment calculation because the main goal of the study is to meet energy targets at the time of construction at minimum cost. The 16 technology parameters considered and their corresponding levels of accomplishment with individual costs based on system size are given in Figure A.6 and A.7.

CHAPTER 3

PRESCRIPTIVE DESIGN GUIDES

Passivhaus:

Passivhaus is self-described as “The world’s leading fabric first approach to low energy buildings”. (passivhaus.org.uk) The Passivhaus ideology and rating system is interesting because it is composed of both prescriptive requirements and a performance rating. The performance rating in this system is set up such that certification can only be awarded after the building is operational, where as this study considers the design specifications. To rate the outcome of the Passivhaus compliant designs in this study the impact of the Passivhaus guidelines on the office and apartment building’s EUI are calculated by EPSCT. (Figure A.3) For the office and apartment buildings in this case study the Passivhaus guidelines required selecting the technologies: slowly rotating heat exchangers, improved sealing (ACH = 0.13/0.20 office/apartment), 139.7mm polystyrene roof insulation, SIP wall panels with 139.7mm polystyrene insulation, and 41mm quadruple glazing. (Figure A.8) The office and apartment buildings recorded a 35.6% and 36.0% energy savings respectively, as a reduction in EUI as calculated by ESPCT. (Figure 3.2) The premium cost to implement the Passivhaus standards over the baseline cost 70.5% more for the office building compared to the apartment building which shows that it is much more expensive to improve fabric of the office buildings compared to the apartment building. (Figure 3.1)

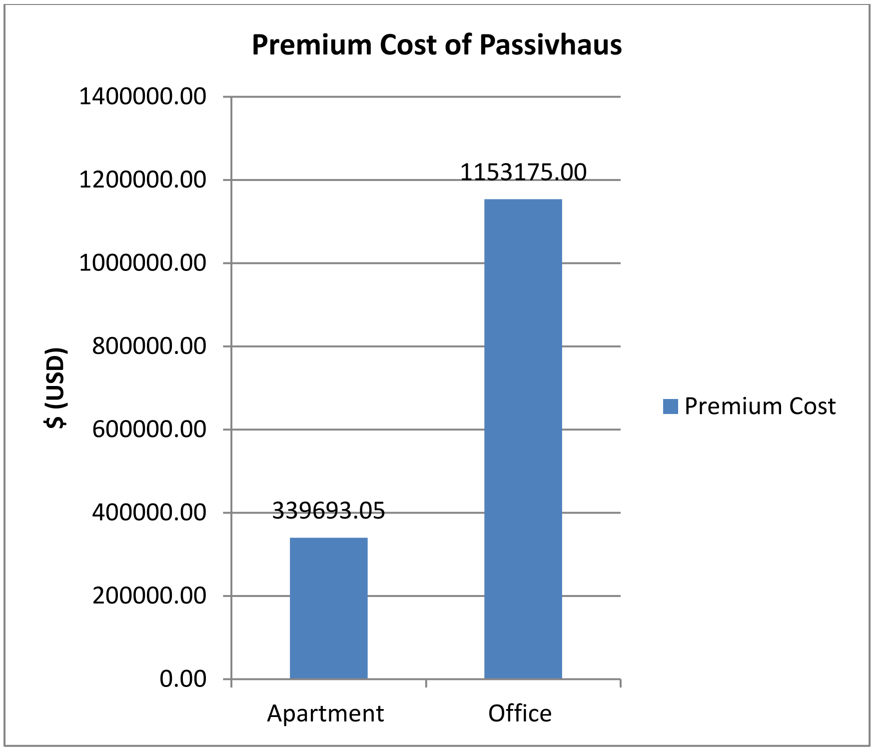

Figure 3.1: Premium Cost of Passivhaus

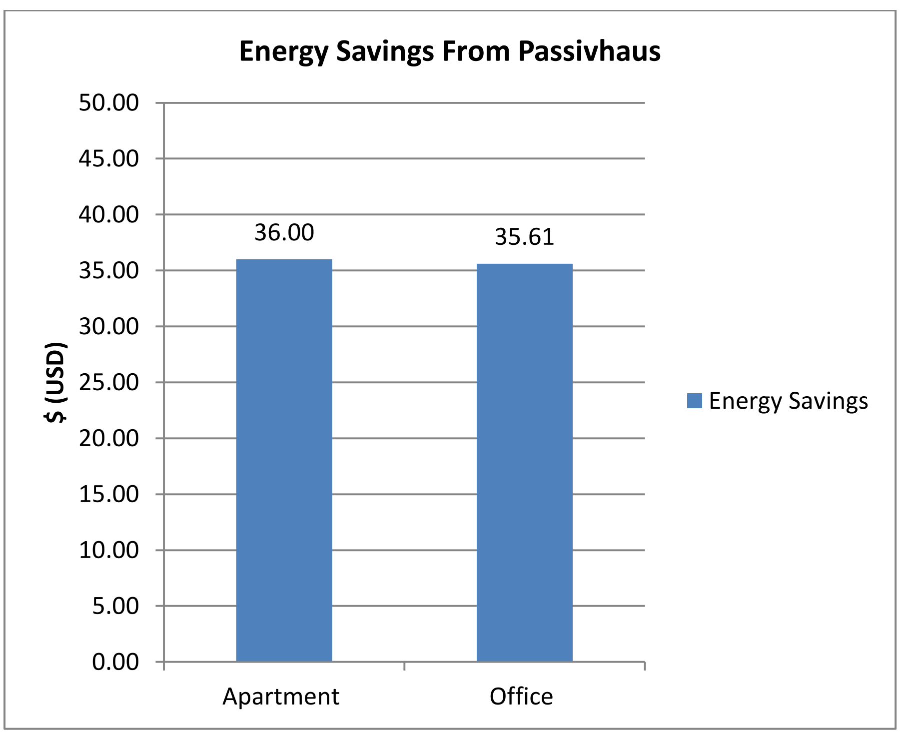

Figure 3.2: Energy Savings from Passivhaus

ASHRAE Advanced Energy Design Guide:

The ASHRAE Advanced Energy Design Guidelines were developed as a prescriptive methodology for small to medium office buildings to achieve 50% energy savings with variations provided for each of the US climate zones. The document also includes conceptual ideas about integrated design frameworks and workflow arrangements that will help facilitate the production of energy efficient buildings. In this case study we assume that the proto-typical Korean apartment and office buildings have been through the design development stage and are being optimized for materials, lighting, and heating and cooling systems so the focus of the application is the specific level of achievement for each of the technology parameter. For this study the recommendations are applied for US climate zone 4, Baltimore, which is a coastal city two degrees of latitude north of the Korean Capital, Seoul. (Figure A.4) Baltimore and Seoul are also considered to be in the same zones from the Koppen-Geiger Climate Classification and are classified as 'Cfa' which is "warm temperate, fully humid, hot summer". (Rubel 2006) The technologies that were required for the apartment and office to meet ASHRAE Energy Design Guide standards are Daylight Sensors, Occupancy Sensors, High Efficiency Boiler for heating and hot water, improved sealants (ACH = 0.13/0.20 office/apartment), Energy Star Equipment, High Efficiency Florescent Lighting, 139.7mm polystyrene roof insulation, SIP wall panels with 88.5 mm polystyrene insulation. (Figure A.8) The office and apartment buildings both recorded a 43.75% and 43.0% reduction in EUI respectively as calculated by ESPCT (Figure 3.4) while the premium cost to implement the ASHRAE design guide standards over the baseline cost 57.5% more for the office compared to the apartment building.

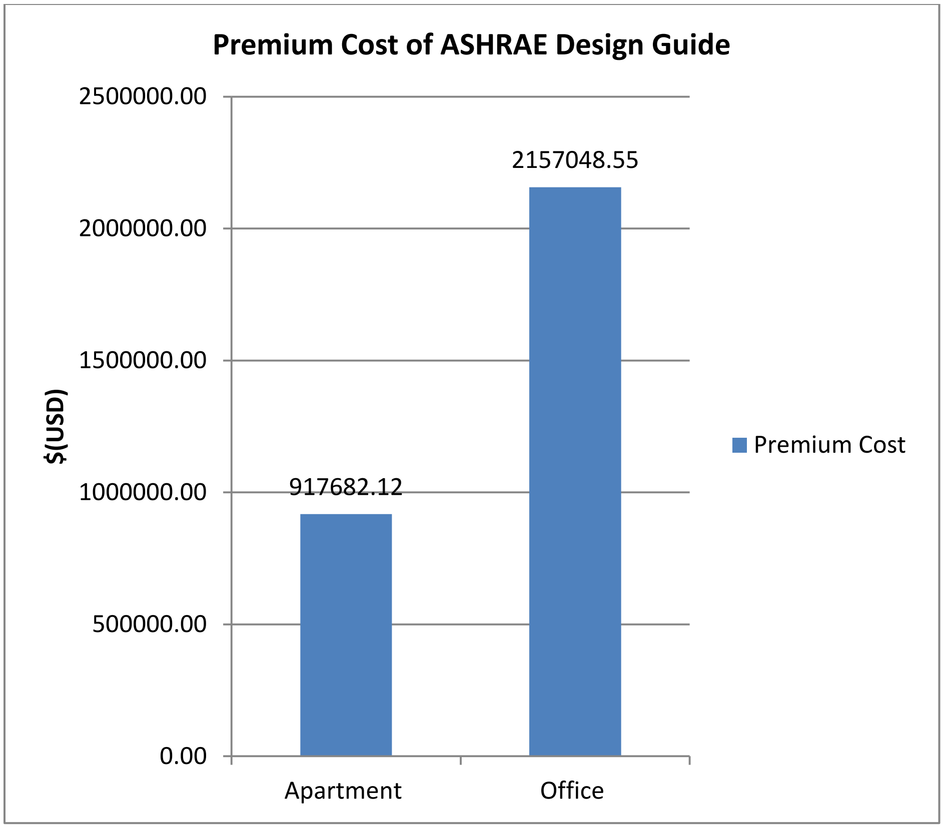

Figure 3.3: Premium Cost of ASHRAE Design Guide

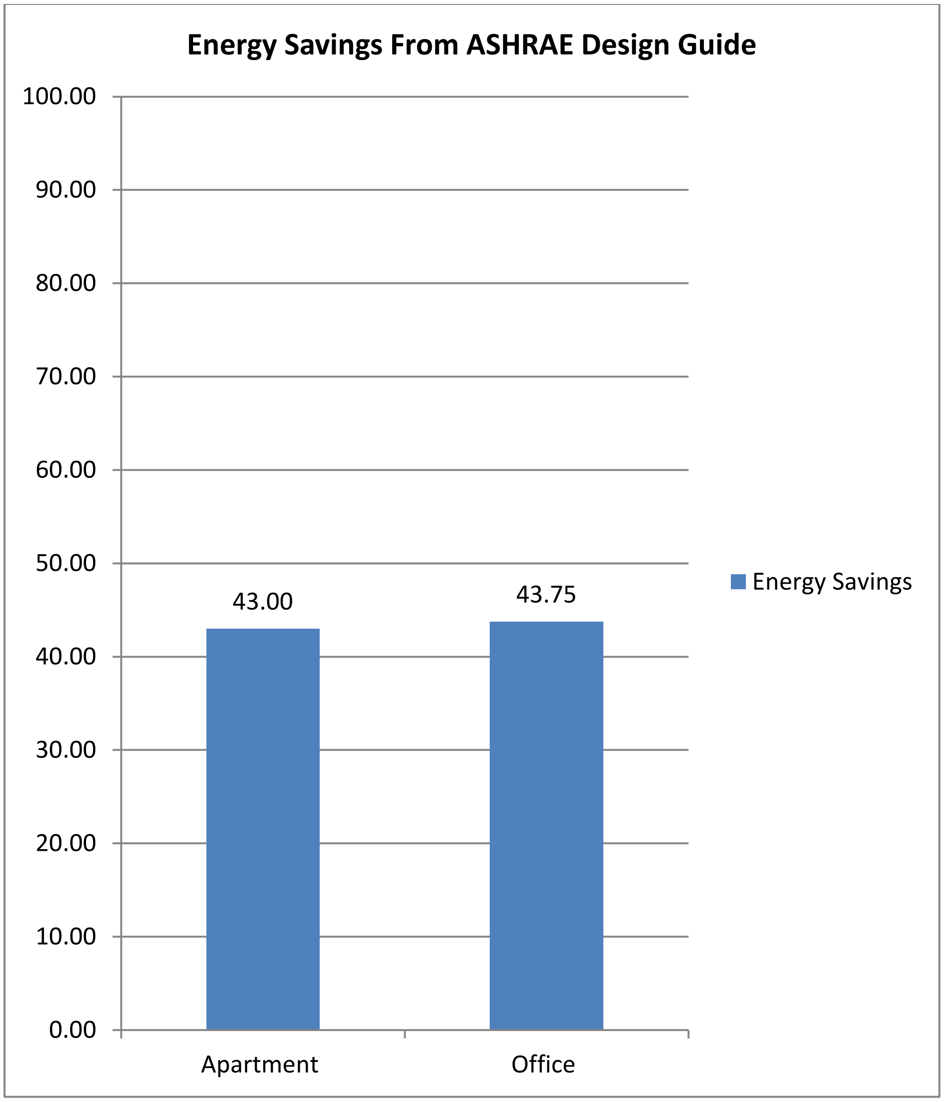

Figure 3.4: Energy Savings from ASHRAE Design Guide

CHAPTER 4

OPTIMIZATION

To search the large discrete combinatorial space of technology alternatives an optimization algorithm is developed into a MATLAB code which automates the testing of combinations of technologies in a descent and combined ascent and descent and method which can be initialized at any point, or specific set combinations to begin the search for an optimum. The final method implemented in this study is the combined ascent-descent procedure which initializes from the baseline building where all technologies are equal to the lowest or baseline level of accomplishment. The algorithm then ascends in steps by selecting the alternative that maximizes the objective function, E/C ratio, until the energy saving target is reached directly or exceeded. When the energy savings target is exceeded the algorithm performs the procedure in reverse; by stepping down levels of accomplishment until the last step would result in the violation of the constraint. In this study the switch to the descent procedure can be seen in Figures 4.1, 4.2, 4.3 and 4.4 has a ridge where the optimization path steps down to reach the final optimization of the E/C Ratio.

The developed combinatorial optimization approach is unlike previous optimization studies because it does not reduce the discrete nature of technology accomplishments by continualizations of a minimum and maximum property values but retains the ability to produce unique solutions from currently available discrete technology options and products. One reason to support the creation of custom MATLAB code for optimization is that even powerful off-the-shelf software such as Phoenix Integration's Model Center is unable to execute optimization algorithms with discrete input parameter values. Even with an automated process in MATLAB the full set of combinatoric options cannot be found because the process is computationally prohibitive; requiring more than 170 million evaluations of the EPSCT in Excel.

The HVAC system in the current optimization does not vary in its thermal heat delivery or removal mechanism, fan coils, but does vary the efficiency of generation mechanism. This allows for a more stable optimization process because the only variable that changes is the coefficient of performance of the system (COP) without changing the delivery dynamics of the system. This process can be still be problematic in finding a global optimum because the effectiveness of the supply side depends on the demand side parameters while the performance of demand side is independent.

The optimization algorithm can be written as:

$C(\boldsymbol{x}) = cost\ function$
$E(\boldsymbol{x}) = energy\ savings\ function$
$\chi = \{0, \ldots, n_1\} \times \cdots \times \{0, \ldots, n_p\}$
$T = minimum\ required\ energy\ savings$
$C(\boldsymbol{x}) = \sum_{i=1}^{p} A_i(x_i)$, where $x_i \in \{0,1, \ldots, n_i\}$ and the A_i's are increasing functions, i.e.,$A_i(x_k) > A_i(x_l)\ if\ k > l$.
Assume that $E(\boldsymbol{0}) \le T \le E\left(\left(n_1, \ldots, n_p\right)^T\right)$ and $E\left(\left(n_1, \ldots, n_p\right)^T\right) = \max\{E(\boldsymbol{x}): \boldsymbol{x} \in \chi\}$.
Optimization Algorithm:
Initialize**:** Specify a starting solution $\boldsymbol{x}_0$. Compute $E(\boldsymbol{x}_0)$. Set $\boldsymbol{x} = \boldsymbol{x}_0$. If $E(\boldsymbol{x}_0) > T$, use Descent Procedure. If $E(\boldsymbol{x}_0) < T$, use Combined Ascent and Descent Procedure.
Descent Procedure:

1. Set $\Omega = \{1, \ldots, p\}$.
2. For $i \in \Omega$, set $\boldsymbol{x}^i = \boldsymbol{x}$. If $x_i^i > 0$, set $x_i^i = x_i^i - 1$ and compute $S(\boldsymbol{x}^i) = E(\boldsymbol{x}^i)/C(\boldsymbol{x}^i)$. Otherwise, set $\Omega = \Omega \backslash \{i\}$.
3. If $\Omega = \emptyset$, **stop** and return $\boldsymbol{x}$. Otherwise, find $k = \operatorname{argmax}\{S(\boldsymbol{x}^i): i \in \Omega\}$.
4. If $E(\boldsymbol{x}^k) \ge T$, set $\boldsymbol{x} = \boldsymbol{x}^k$ and return to Step 2. Otherwise, set $\Omega = \Omega \backslash \{k\}$ and return to Step 3.

Combined Ascent and Descent Procedure:

1. Set $\Omega = \{1, \dots, p\}$.
2. For $i \in \Omega$, set $\boldsymbol{x}^i = \boldsymbol{x}$. If $x_i^i < n_i$, set $x_i^i = x_i^i + 1$ and compute $S(\boldsymbol{x}^i) = E(\boldsymbol{x}^i)/C(\boldsymbol{x}^i)$. Otherwise, set $\Omega = \Omega \backslash \{i\}$.
3. Find $k = \text{argmax}\{S(\boldsymbol{x}^i): i \in \Omega\}$ and set $\boldsymbol{x} = \boldsymbol{x}^k$.
4. If $E(\boldsymbol{x}^k) \geq T$, find $l = \text{argmin}\{C(\boldsymbol{x}^i): i \in \Omega, E(\boldsymbol{x}^i) \geq T\}$, and set $\boldsymbol{x} = \boldsymbol{x}^l$. Otherwise, return to Step 2.
5. Apply Descent Procedure with $\boldsymbol{x}$ as starting point.

(Tan 2012)

Optimization Results:

The energy saving targets for the optimization are set for 30% and 50% of the EUI for the proto-typical apartment and office building as constraints with the minimization of the premium cost function. Analysis of the optimization routine shows that the algorithm selects more photovoltaics to generate renewable energy in the middle of the routine but after the building envelope's level of accomplishment is raised the value of some of the photovoltaics diminishes and they are removed during the descent procedure.

The ridge at the end of the optimization procedure seen in each of the four optimization graphs, Figure 4.1 – 4.4, are sets that are very close to the optimal point but are where technology accomplishment levels can still be decreased. The procedure steps down until the energy target will be violated if and other technology accomplishment levels are decreased. This study considers that all the technologies included in the optimization are equally preferable to the decision maker such that even though the technology combinations on the ridge of the final descent procedure are very close to the optimum the point the solution that maximizes the objective function E/C Ratio subject to the constrained savings target is the one selected.

The optimization process resulted in more balanced premium cost for the apartment and office buildings compared to the Passivhaus and ASHRAE energy design guide methodologies. For the 30% energy saving target the office building required 25% more in premium cost compared to the apartment building and for the 50% energy savings target the office required 28% more in premium cost than the apartment building.

The technology parameters that the optimization selected for the 30% energy savings target apartment building are improved sealants (ACH = 0.20), Energy Star appliances, Double Low-E Glazing, and Solar Hot-Water installed on 25% of the roof area. The optimization algorithm selected improved sealants (ACH = 0.13), Energy Star equipment, and Triple Low-E Glazing for the office buildings 30% energy savings target. In the optimization process to reach the 50% energy savings target for the apartment building the algorithm selected Occupancy Sensors, Dimmer Switches, Rotating Heat Exchangers, improved sealants (ACH = 0.20), Photovoltaics on 25% of the roof area, Energy Star Equipment, T-10 Florescent Lighting, SIP wall panels with 190.5mm polystyrene insulation, Triple Low-E Windows, Solar Hot Water on 25% of the roof area. In the optimization process to reach the 50% energy savings target for the office building the algorithm selected Dimmer Switches, 20% Exhaust Air Recirculation, improved sealants (ACH = 0.13), Energy Star Equipment, 139.7mm Extruded Polystyrene Roof Insulation, 203.2mm Insulated Concrete Form Work, and 41mm Quadruple Glazing. (Figure A.8)

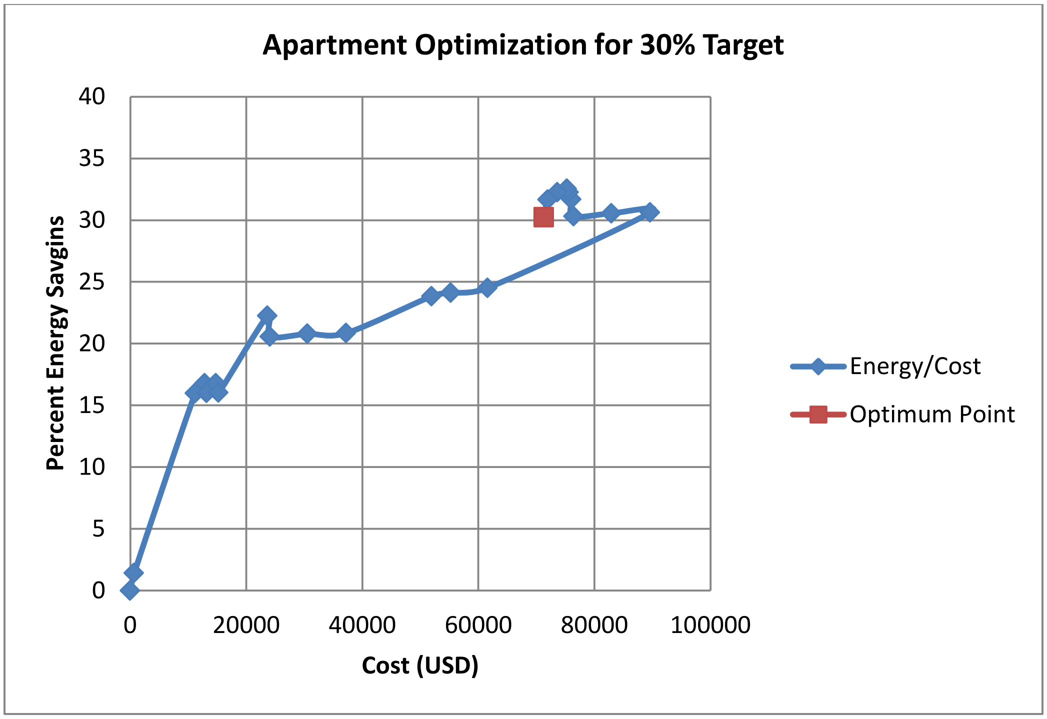

Figure 4.1: Apartment Optimization for 30% Target

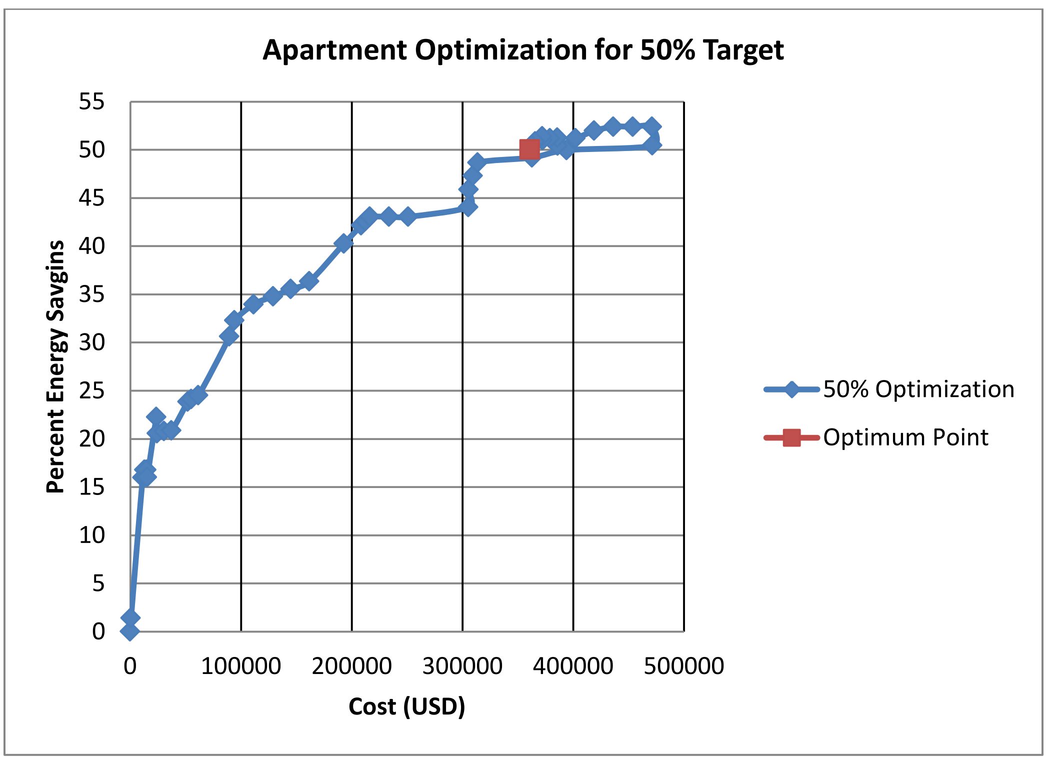

Figure 4.2: Apartment Optimization for 50% Target

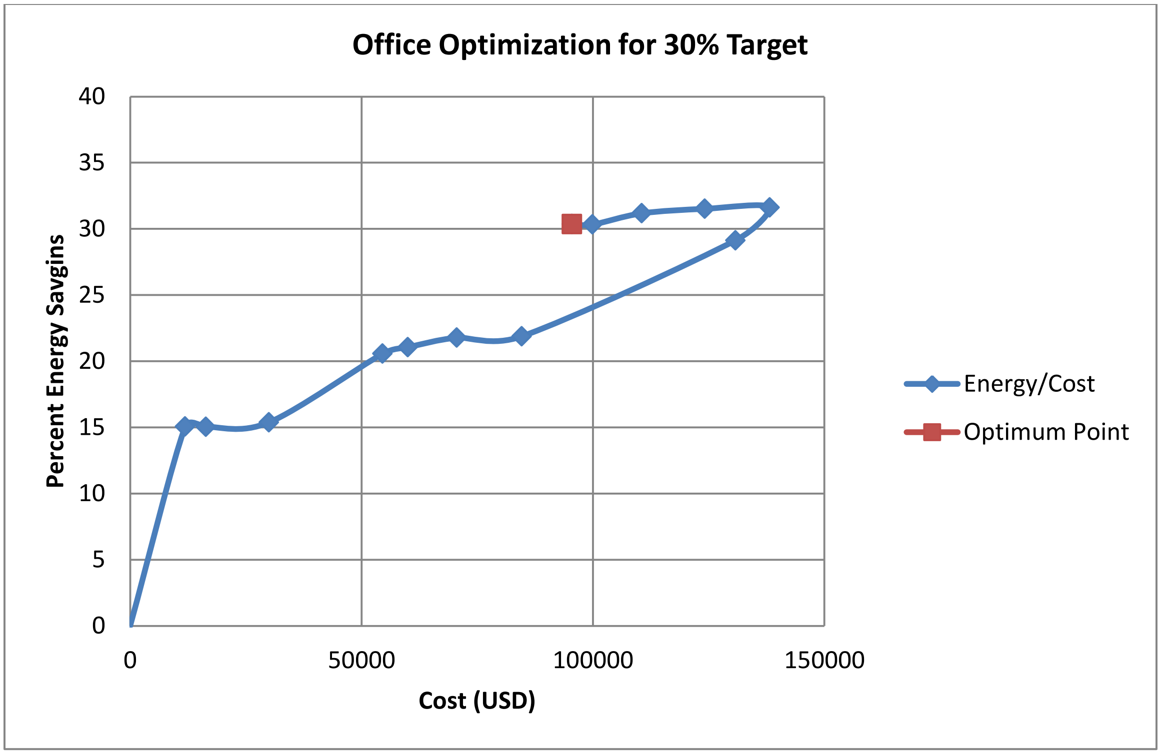

Figure 4.3: Office Optimization for 30% Target

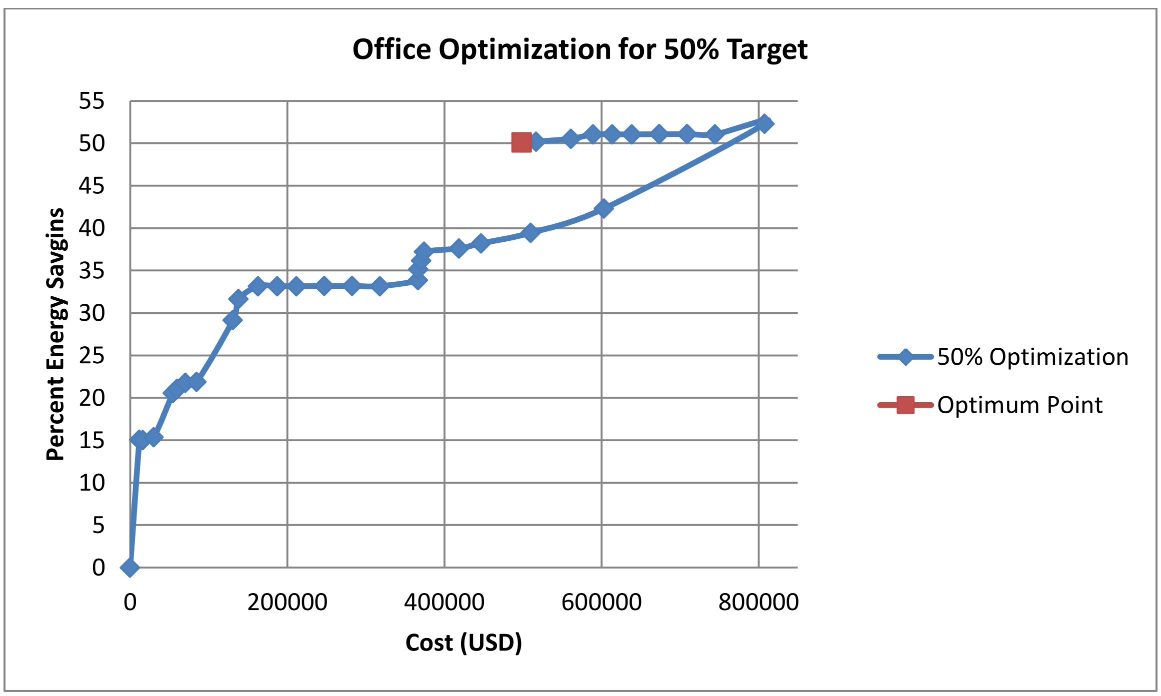

Figure 4.4: Office Optimization for 50% Target

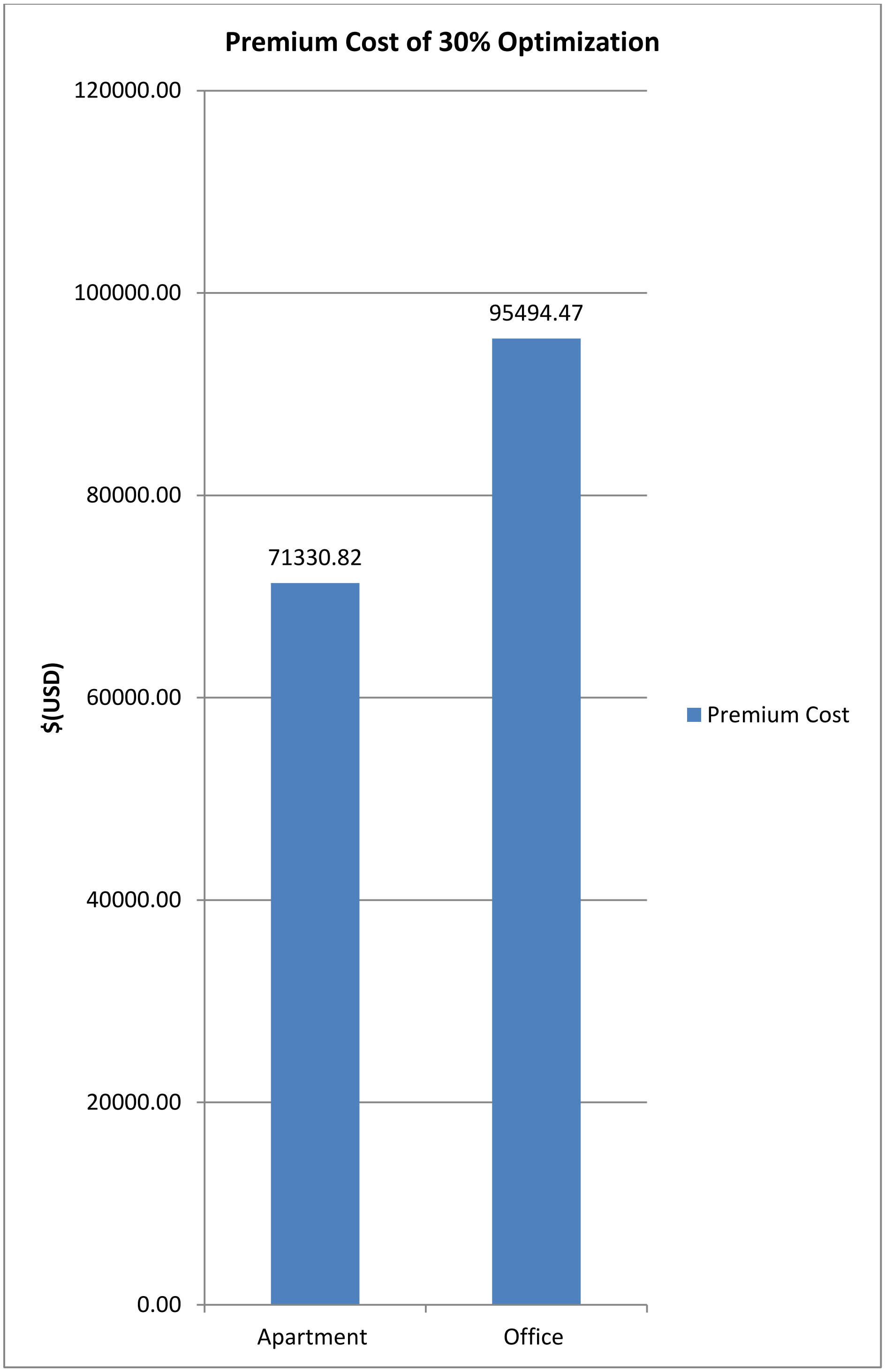

Figure 4.5: Premium Cost of 30% Optimization

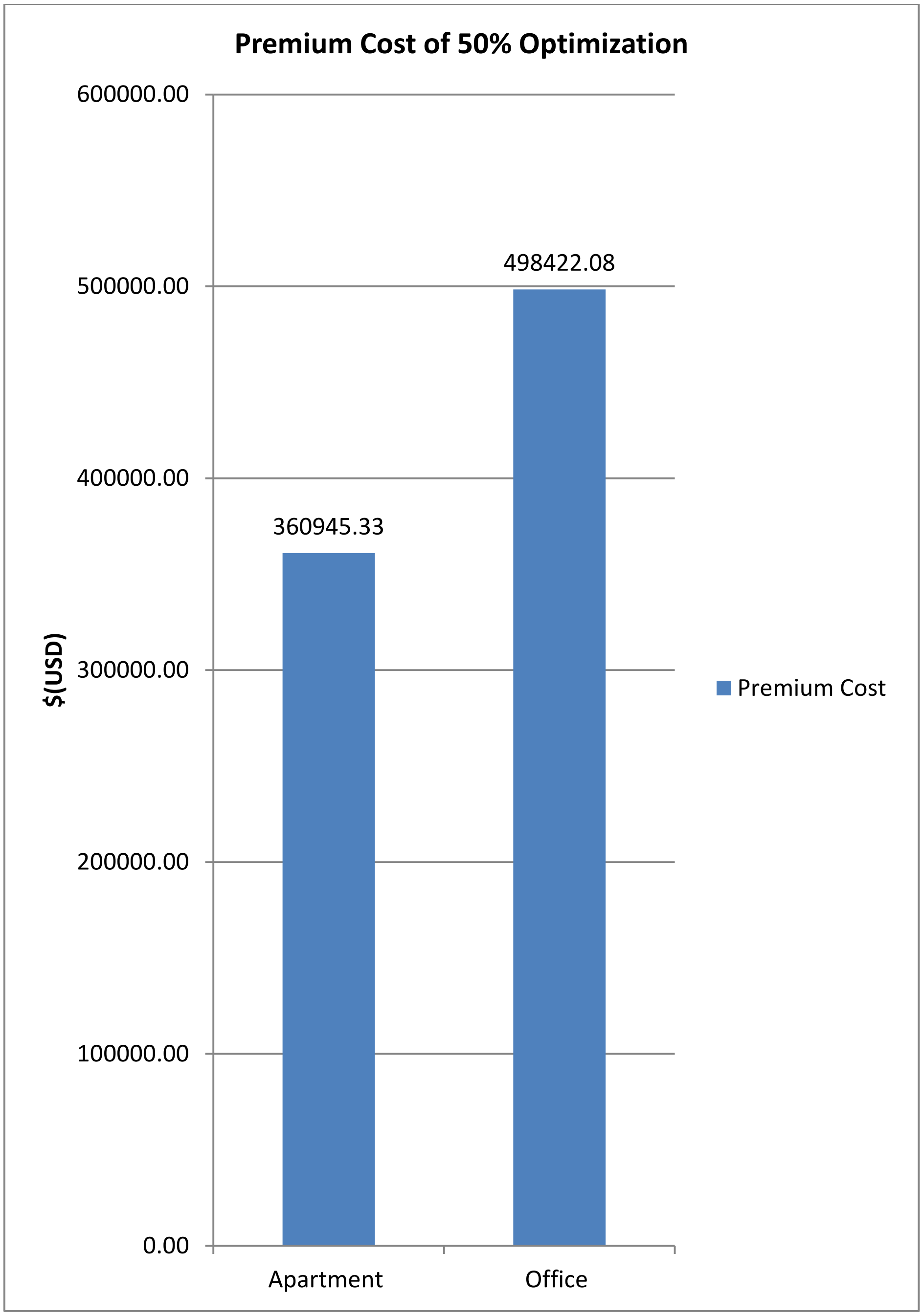

Figure 4.6: Premium Cost of 50% Optimization

Cost Ranking Procedure:

The cost ranking procedure is a simplified algorithm used as a benchmark to evaluate the effectiveness of the optimization methodology. The cost ranking procedure is based on the same motivation as the optimization algorithm, which is to achieve an energy savings target at the lowest level of premium cost, but unlike the optimization process which computes a search direction the cost ranking procedure's evaluation is fixed by ranking the all the technology parameters from lowest to highest premium cost. The cost ranking procedure continually steps up in levels of technology achievement from the baseline until the energy saving target is reached or over stepped. Since this process is inherently blind to the interactions of the technology parameters it performs worse than the optimization algorithm at finding an absolute minimum. In contrast to the complete ascent-descent optimization algorithm's outcome which can vary based on the initialization point the cost ranking procedure is a good method for comparison because its unique solution can always be found for any set of technology parameters of a given building thus its outcome it derived from set based logic rather than a combinatoric.

To reach the 30% energy saving target in the apartment building the cost ranking method selected Dimmer Switches, Daylight Sensors, Occupancy Sensors, Solar Hot Water on 25% of the roof area, improved sealants (ACH = 0.2), 190.5mm Polystyrene Roof Insulation, 20% Exhaust Air Recirculation, Photovoltaic Modules on 25% of the roof area, Energy Star Appliances and Double Low-E Glazing. To reach the 50% energy saving target in the apartment building the cost ranking method selected Dimmer Switches, Daylight Sensors, Occupancy Sensors, Solar Hot Water on 25% of the roof area, improved sealants (ACH = 0.2), 190.5mm Polystyrene Roof Insulation, 60%

Exhaust Air Recirculation, Photovoltaic Modules on 75% of the roof area, Energy Star Appliances, Triple Low-E Glazing, Rotating Heat Exchangers, T-10 Florescent Lighting, SIP wall panels with 139.7mm polystyrene insulation. (Figure A.8)

To reach the 30% energy saving target in the office building the cost ranking method selected Solar Hot Water on 25% of the roof area, improved sealants (ACH = 0.13), 20% Exhaust Air Recirculation, 190.5mm Polystyrene Roof Insulation, Photovoltaic Modules on 25% of the roof area, Energy Star Equipment and Double Low-E Glazing. To reach the 50% energy saving target in the office building the cost ranking method selected Solar Hot Water on 25% of the roof area, improved sealants (ACH = 0.13), 60% Exhaust Air Recirculation, 190.5mm Polystyrene Roof Insulation, Photovoltaic Modules on 75% of the roof area, Energy Star Equipment, Triple Low-E Glazing, High Efficiency Electric Boiler, Dimmer Controls, SIP wall panels with 139.7mm polystyrene insulation, and T-10 Florescent Lighting. Figure (A.8)

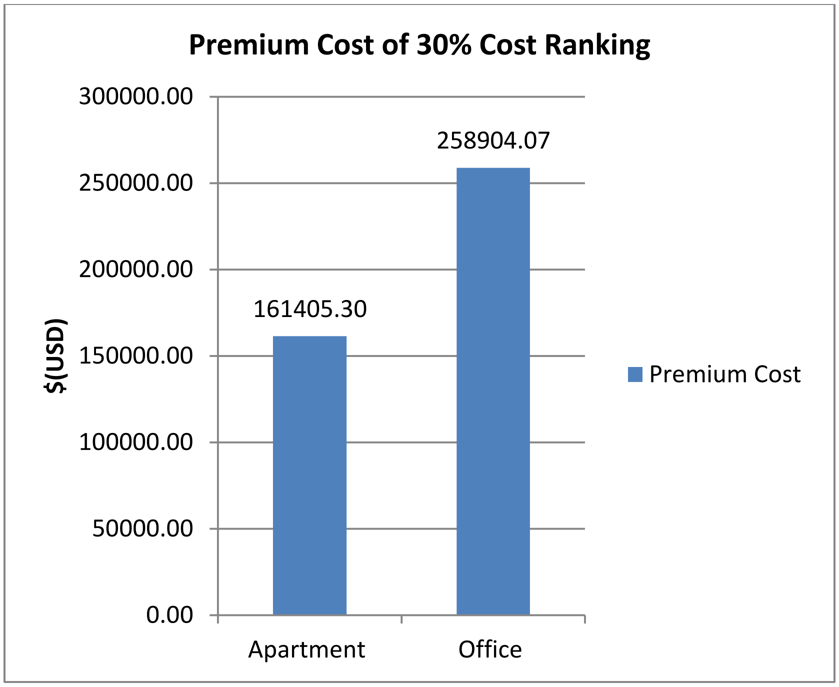

Figure 4.7: Premium Cost of 30% Cost Ranking

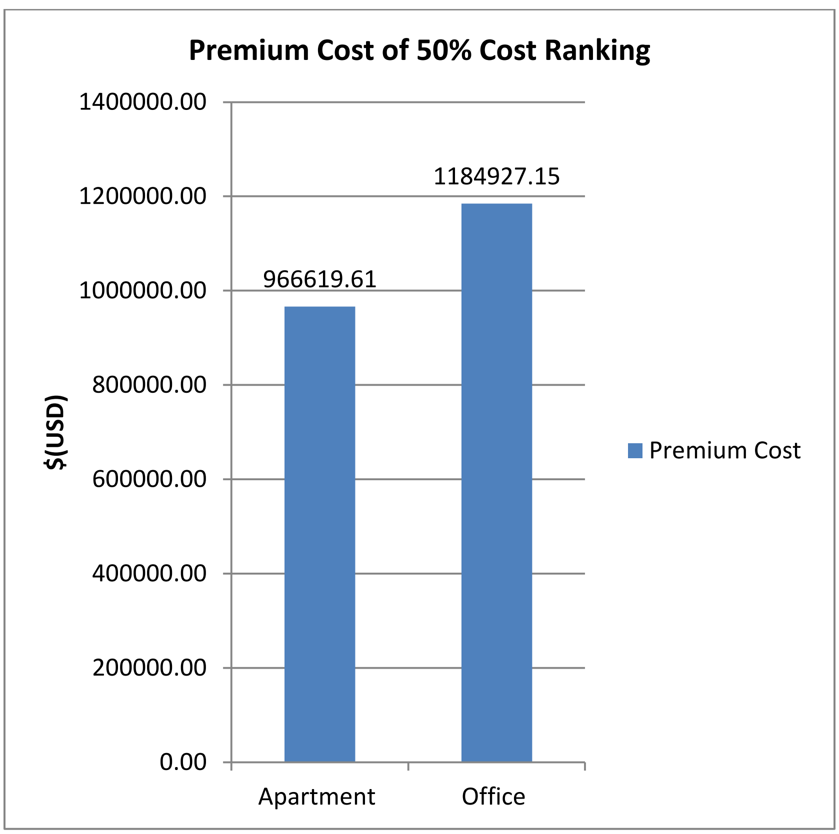

Figure 4.8: Premium Cost of 50% Cost Ranking

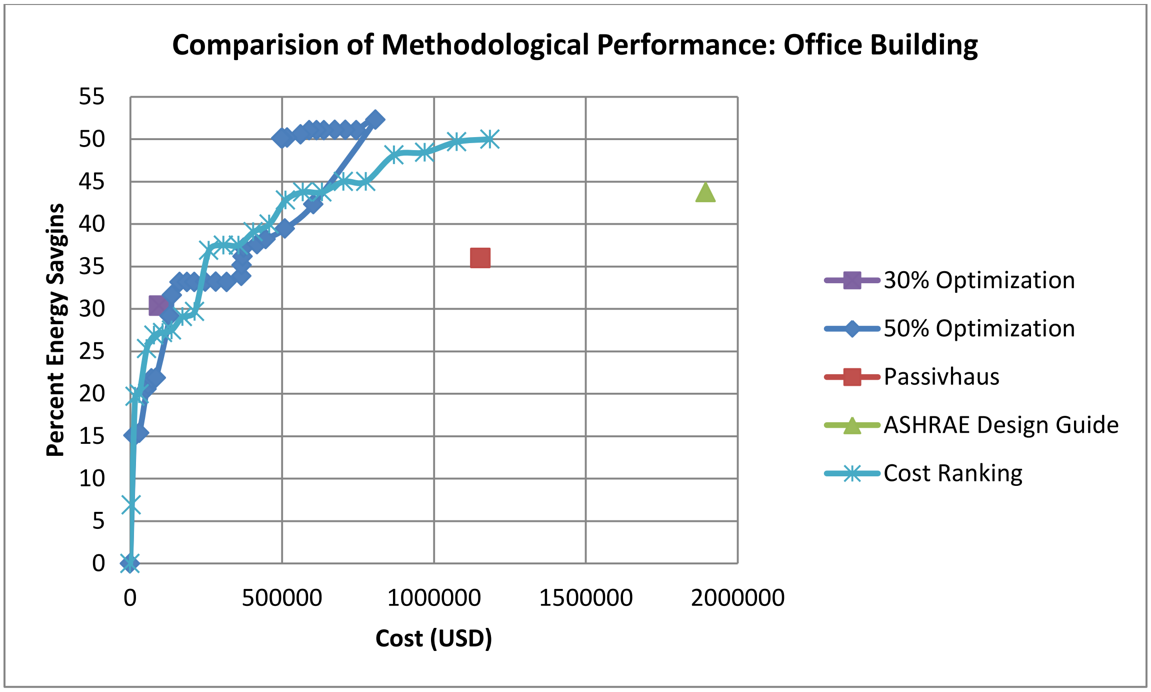

Figure 4.9: Comparison of Methodological Performance: Office Building

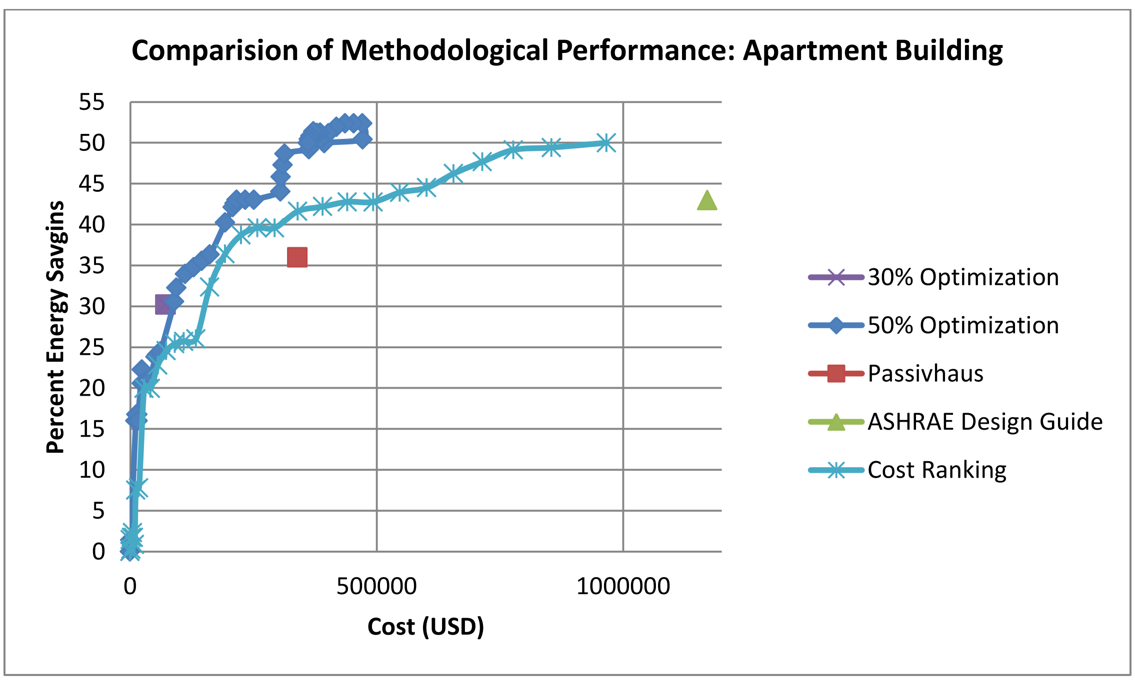

Figure 4.10: Comparison of Methodological Performance: Apartment Building

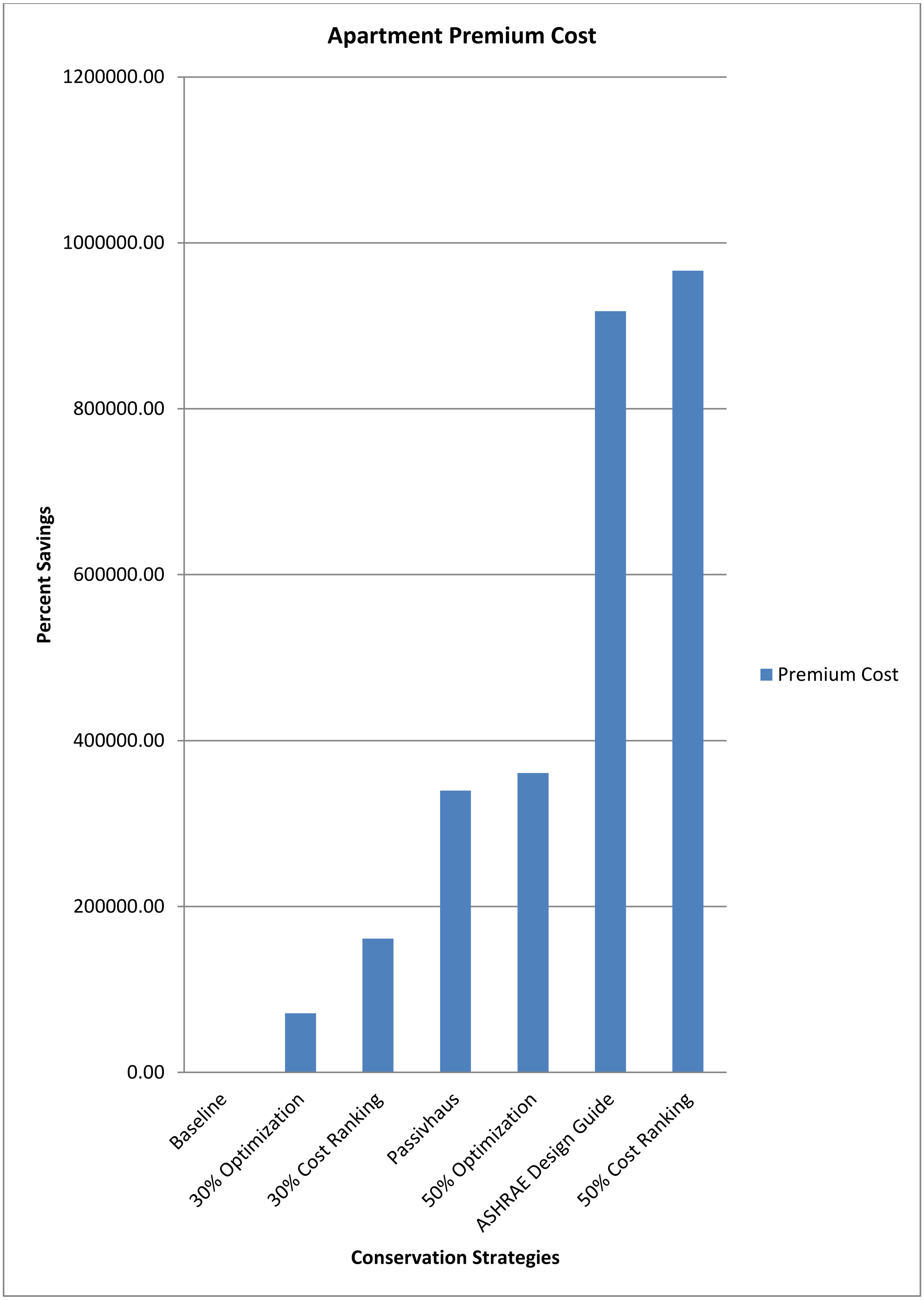

Figure 4.11: Apartment Premium Cost

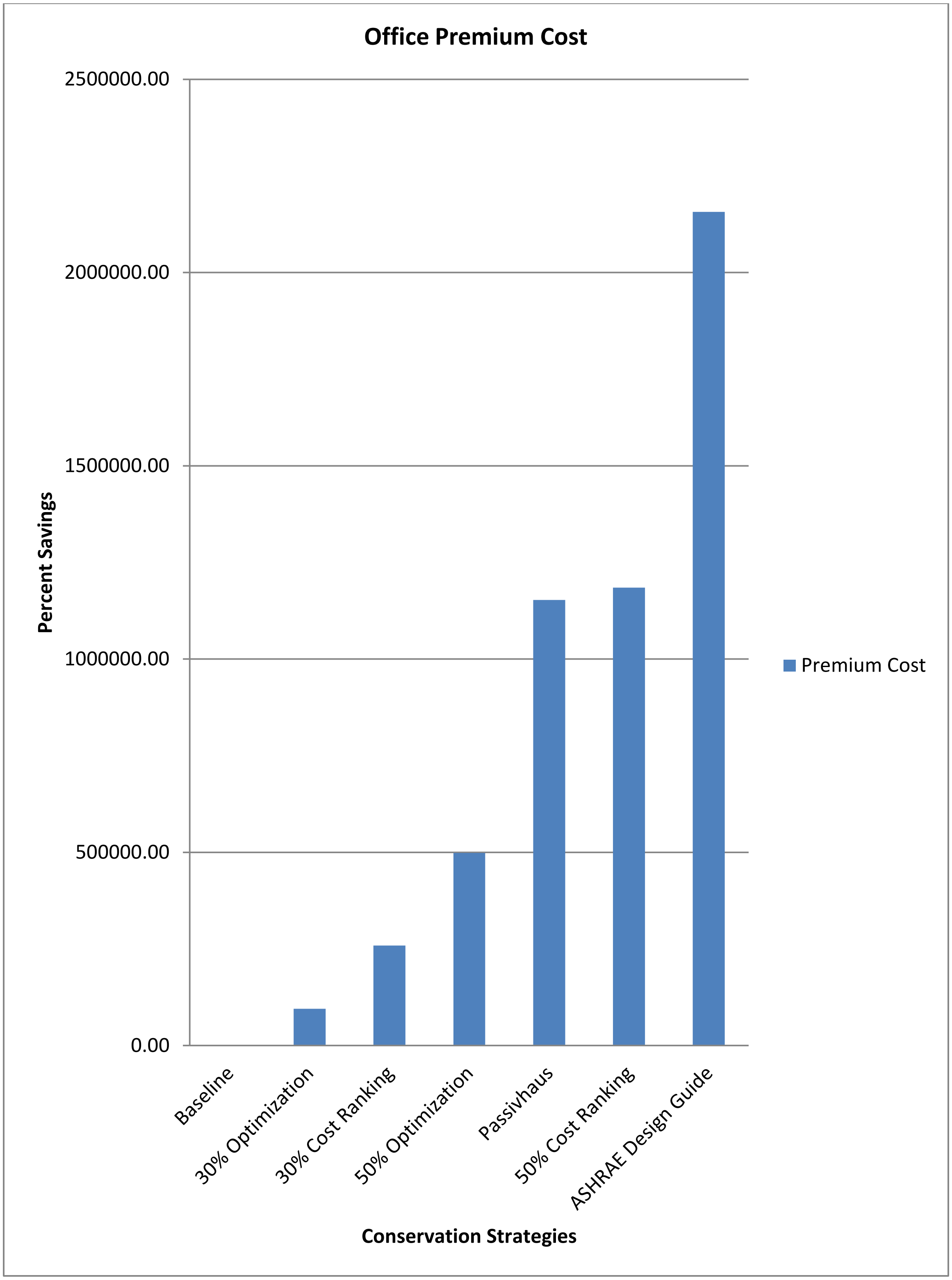

Figure 4.12: Office Premium Cost

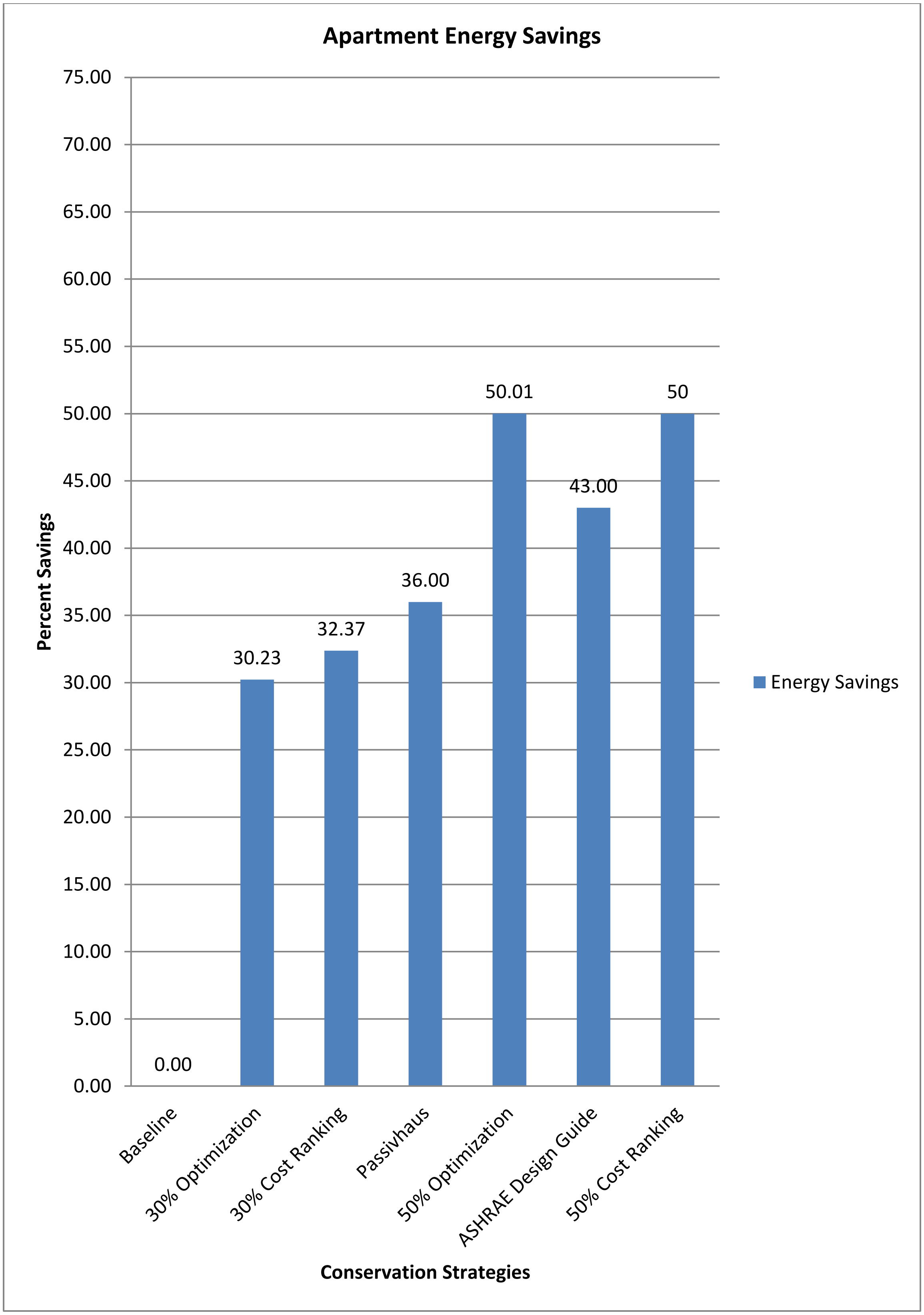

Figure 4.13: Apartment Energy Savings

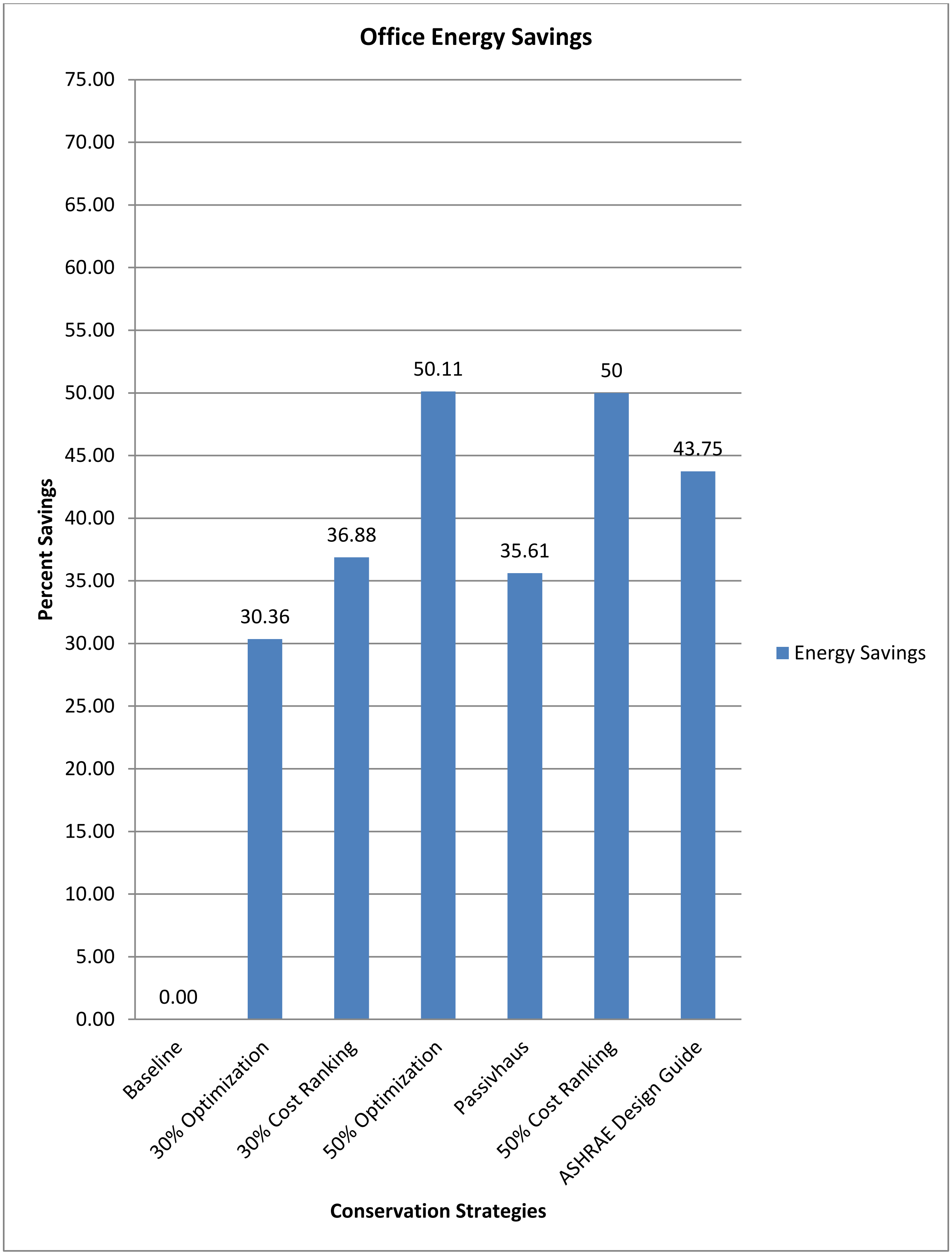

Figure 4.14: Office Energy Savings

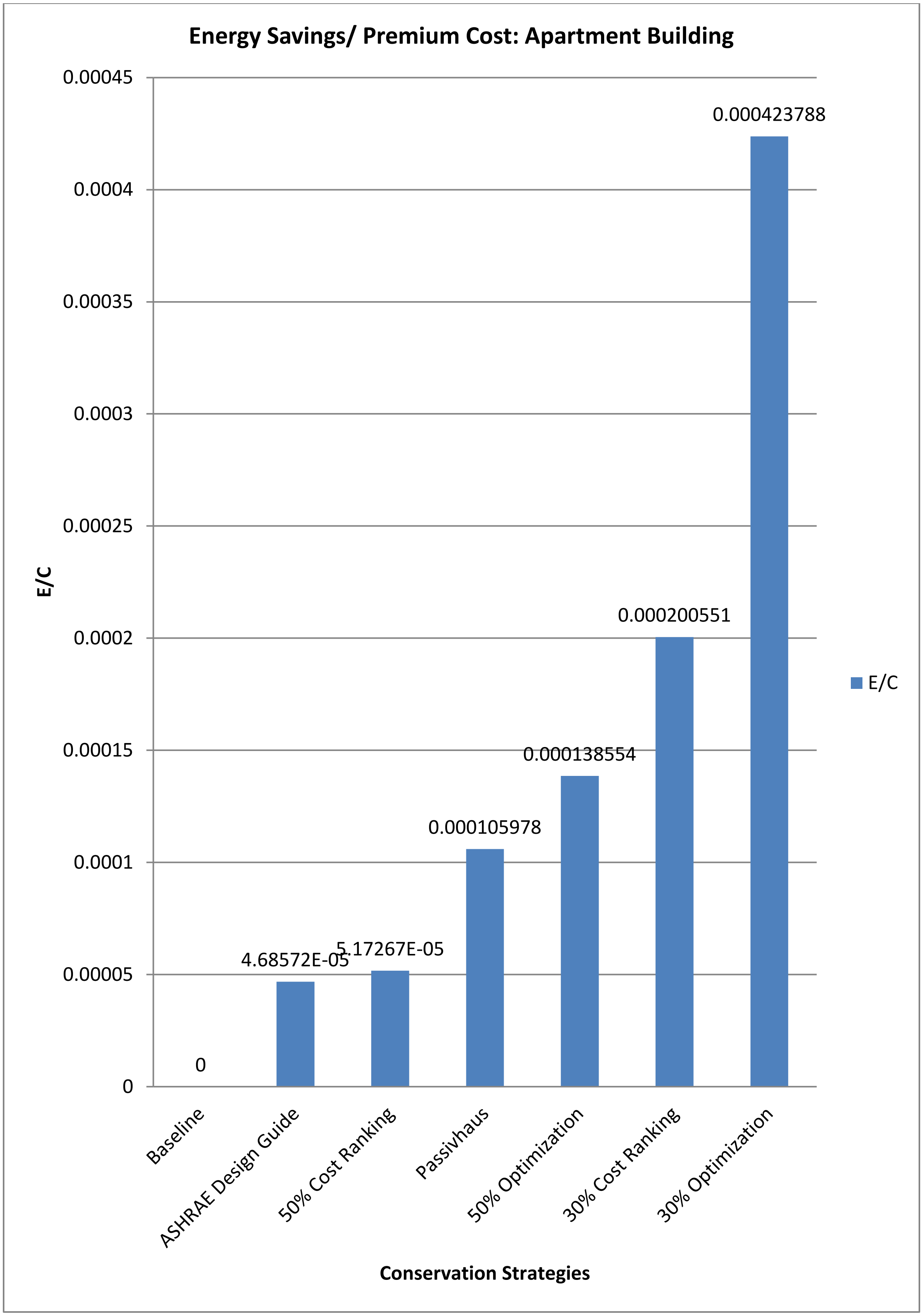

Figure 4.15: Energy Savings/ Premium Cost: Apartment Building

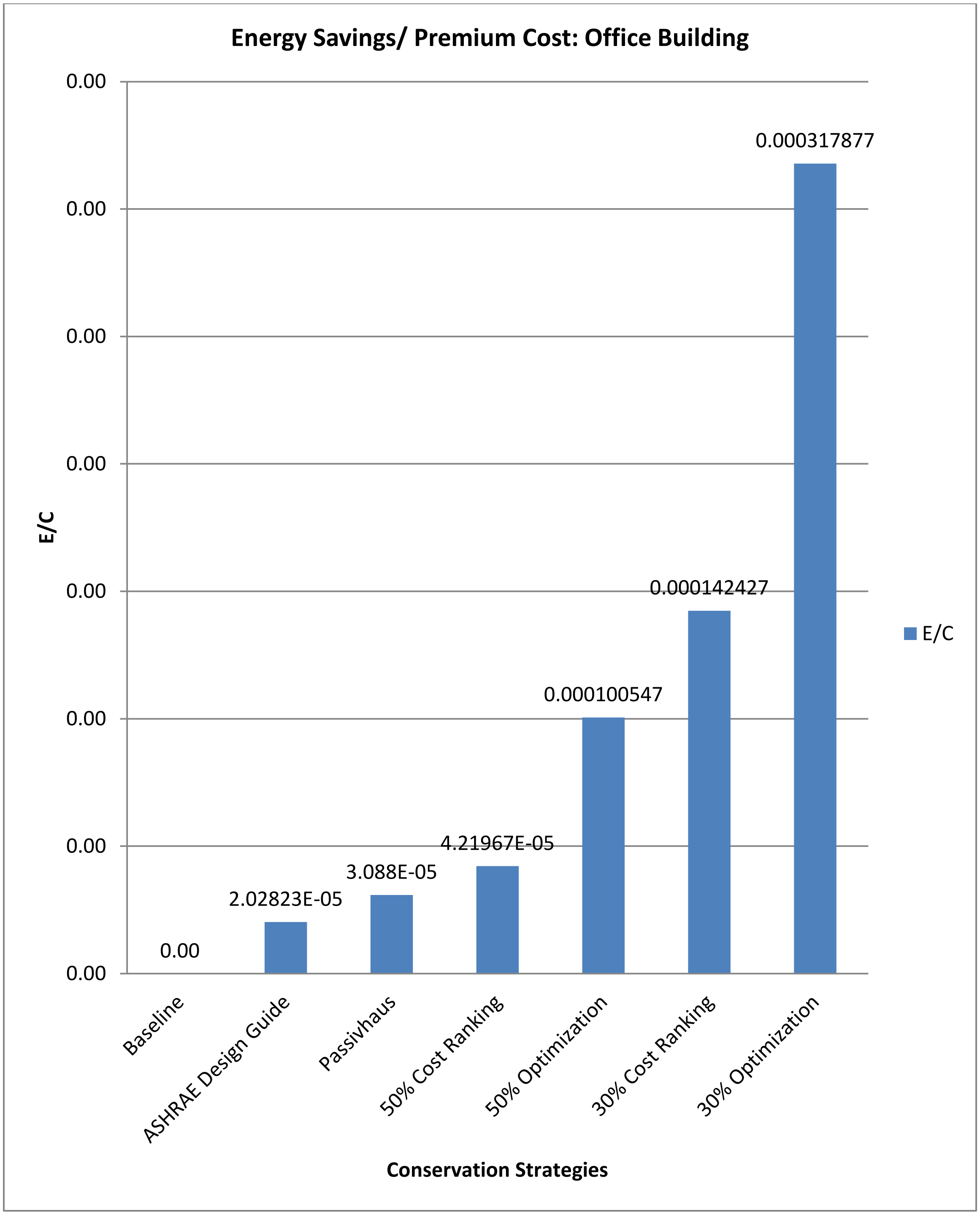

Figure 4.16: Energy Savings/ Premium Cost: Office Building

CHAPTER 5

CONCLUSION

Since the objective of the optimization algorithm is to maximize the ratio of energy savings divided by cost (E/C) this can also become a metric to measure the performance of an energy saving methodology. The evaluation of (E/C) applied to both the apartment and office building show that the ranking from most efficient methodology at saving energy at the lowest premium cost goes from 30% Optimization, 30% Cost Ranking, 50% Optimization, Passivhaus, 50% Cost Ranking, and ASHRAE design guide. This shows that the prescriptive methodologies are much less efficient than the optimization algorithm at reducing the proto-typical building's EUI at the lowest premium cost. (Figure 4.15 and 4.16) In comparison of the optimization method to the cost ranking procedure at the 30% energy savings target; the optimization is 55.8% less in premium cost for the apartment building and 63.1% less for the office building. At the 50% energy savings target the optimization is 62.7% less in premium cost for the apartment building and 57.9% less for the office building. (Figure 4.11 and 4.12)

Therefore the optimization methodology is shown to produce the best performance in terms of finding the lowest cost solutions to energy saving targets for the proto-typical apartment and office buildings. This result further reinforces the concept of performance based thinking in that the performance indicator, EUI, is a function of all the building parameters and can only be optimized at the whole building level rather than sub-optimizing technology components. Furthermore, this result identifies the weaknesses of prescriptive energy saving methodologies in that they do not provide cost efficient solutions to meet the energy saving targets imposed by owners or international energy codes. (Figure 4.9 and 4.10)

Further Applications:

This tool can also be used to study hypothetical situations based on trends in technology development and price forecasting. The tool can be used to answer the questions of how much will the cost of a certain technology have to fall before its selection is advantageous over others. The optimization process could be used by governments and to create more performative based energy codes so building owners can have more alternatives than those listed in the code to develop energy efficient buildings. In the briefing and developing requirements stage the optimization process could also be used to determine appropriate energy saving targets given the owner's budget for premium energy conservation measures. The optimization algorithm would also benefit from more development in the normative calculation such as the ability to represent the thermal storage capacity of solar thermal for space heating as well as a broader range of heat delivery mechanisms such as radiant flooring.

The optimization tool could be even more powerful and widely applicable if cost data were published by manufacturers as openly as the physical characteristics their systems. If the availability of cost data increased then it would be possible to make more accurate longitudinal projection for cost increases such that Net-Present Value could be transparently calculated along with the lifetime cost of energy of the building. These lifetime costs could then be aggregated to find total operations and maintenance for each technology combination.

The results from the optimization can be used to make predictions about which combinations will produce cost-optimal solutions in buildings of similar size, type, function, and climate given a palette of technology parameters and cost information. The results could also be extended to select technologies for retro-fit strategies if the optimization was performed on a normative model that was calibrated to represent the existing buildings. The optimization methodology would also produce a more cost-effective path to bringing existing buildings up to levels of code compliance than generic prescriptive guidelines.

If the existing optimization algorithm in MATLAB code and excel calculator were converted into java then the entire optimization process could become a web based system which is operated on project basis to be directly evaluated by design teams with a set of technology alternatives at different levels of accomplishment and the corresponding monetary cost of each alternative. The optimization will produce the most accurate results if the design team could acquire actual quotes for each technology option for the specific design in question which would account for the specific rationality and construction market at the time of analysis.

The optimization tool would be useful at the briefing stage, as well the design development phase, when the overall building geometry and orientation has been set and material systems have not yet been fully specified. In this case the optimization would be implemented at the end of the design development stage to meet energy saving targets for code compliance.

APPENDIX

Korean Standards for Envelope Conductivity			
	Roof U-Value W/m^{2}K	Wall U-Value W/m^{2}K	Window U-Value W/m^{2}K
Central Region	0.2	0.36	2.1
Southern Region	0.24	0.45	2.4
Jeju Island Region	0.29	0.58	3.1

Figure A.1: Korean Standards for Envelope Conductivity

Apartment Occupancy Schedule		
Hour	Occ_WD	Occ_WE
0-1	0.20	0.20
1-2	0.05	0.05
2-3	0.02	0.02
3-4	0.02	0.02
4-5	0.05	0.05
5-6	0.10	0.10
6-7	0.32	0.20
7-8	0.65	0.45
8-9	0.55	0.51
9-10	0.50	0.70
10-11	0.45	0.65
11-12	0.45	0.65
12-13	0.50	0.65
13-14	0.45	0.60
14-15	0.45	0.60
15-16	0.50	0.65
16-17	0.65	0.70
17-18	0.75	0.75
18-19	0.85	0.80
19-20	0.85	0.80
20-21	0.85	0.78
21-22	0.70	0.75
22-23	0.40	0.40
23-24	0.25	0.45

Figure A.2: Apartment Occupancy Schedule

	Roof U-Value (W/m^2K)	Wall U-Value (W/m^2K)	Window U-Value (W/m^2K)	MVHR (effficiency)	ACH
Passivhaus Standards	0.15	0.15	0.85	0.75	0.6

Figure A.3: Passivhaus Standards

	Roof U-Value (W/m^2K)	Wall U-Value (W/m^2K)	Window U-Value (W/m^2K)	MVHR (effficiency)	Inflitration ($m^3/h/m^2$)
ASHRAE Standards	0.19	0.28	2.1	0.75	0.0068
	Lighting (W/m^2)	Daylight Sensor	Occupancy Sensor	Energy Star	Bolier (Efficiency)
	7.5	Yes	Yes	Yes	0.9

Figure A.4: ASHRAE Standards

System Sizing	
Type of System	Sizing Methodology
Heating & Cooling	System is sized generically by square meter and does not take advantage of demand side reductions
Photovoltaic	The total roof area is broken up in to four discrete intervals of 25%, 50%, and & 75%
Solar Boiler	The total roof area is broken up in to one discrete intervalof 25%

Figure A.5: System Sizing

APARTMENT PARAMETRIC DATA Figure.5			Cost (USD)	Premium Cost	(0<= factor= <1)		
	Lighting Daylighting Sensor (# of units)	Cost1 = $/m^2	An	Am			
A0 Baseline Daylight Sensor (NULL)	60	0	0	0	1		
A1 Partial Daylight Sensor	60	27.25	1635	1635	0.5		
A2 Fully Automated Daylight Sensor	60	34.48	2068.8	2068.8	0.9		
	Lighting Occupancy Sensor (# of units)	Cost2 = $/m^2	Bn	Bm	(0<= factor= <1)		
B0 Baseline Occupancy Sensor (NULL)	60	0	0	0	1		
B1 Partial OccupancySensor	60	27.25	1635	1635	0.5		
B2 Fully Automated Occupancy Sensor	60	34.48	2068.8	2068.8	0.9		
	Lighting Dimmer Controls (# of units)	Cost3 = $/units	Cn	Cm	(0<= factor= <1)		
C0 Baseline Dimmer Switch (NULL)	60	0	0	0	1		
C1 Partial Dimmer Switch	60	11.03	661.8	661.8	0.5		
C2 Full Dimmer Switch	60	16.54	992.4	992.4	0.9		
	Conditioned Area in m^2	Cost4 = $/m^2	Dn	Dm	Heating COP	Cooling COP	
D0 Two-Pipe FCU, Standard Boiler and Chiller	6028	337.41	2033907.48	0	0.75	2.8	
D1 Two-Pipe FCU, Improved Boiler	6028	384	2314752	280844.52	0.85	3.2	
D2 Two-Pipe FCU, Air Source Heat Pump	6028	435.88	2627484.64	593577.16	1	3.5	
D3 Two-Pipe FCU, Ground Source Heat Pump	6028	784	4725952	2692044.52	3.4	4.25	
	# of units	Cost5 = $/m^2	En	Em	Efficiency Rating		
E0 Baseline Heat Recovery (NULL)	60	0	0	0	0		
E1 Loading Cold with Air-Conditioning	60	519	31140	31140	40%		
E2 Two-Elements-System	60	778.5	46710	46710	60%		
E3 Heat Exchange Plates or Pipes	60	843.38	50602.8	50602.8	65%		
E4 Slowly Rotating or Intermittent Heat Exchangers	60	908.26	54495.6	54495.6	70%		
	# of units	Cost6 = $/units	Fn	Fm	Efficiency Rating		
F0 Exhaust Air Recirculation (NULL)	60	0	0	0	0		
F1 Exhaust Air Recirculation (20%)	60	290.14	17408.4	17408.4	20%		
F2 Exhaust Air Recirculation (40%)	60	580.28	34816.8	34816.8	40%		
F3 Exhaust Air Recirculation (60%)	60	870.42	52225.2	52225.2	60%		
	Envelope Area in m^2	Cost7 = $/m^2	Gn	Gm	m^3/h/m^2		
G0 Baseline Air Tightness - Medium (Q4Pa 1.1 m3/h/m2)	5720.2	1.5	8580.3	0	1.2		
G1 Baseline Air Tightness - Low (Q4Pa 0.6 m3/h/m2)	5720.2	3.34	19105.468	10525.168	0.6		
	# of units	Cost8 = $/units	Hn	Hm	Efficiency Rating		
H0 Baseline Stanfard Boiler	60	3100	186000	0	61%		
H1 Electric Boiler	60	6200	372000	186000	75%		
H2 Co-Generation Boiler	60	7440	446400	260400	90%		
	Conditioned Area in m^2	Cost9 = $/m^2	In	Im	BEMS Class Rating		
I0 Building Energy Management System (NULL)	6028	0	0	0	1		
I1 User Adaptive BEMS	6028	50	301400	301400	2		
I2 Controller Optimized BEMS	6028	75	452100	452100	3		
I3 Fault Detection Diagnosis BEMS	6028	100	602800	602800	4		
	Roof Area m^2	Cost10 = $/m^2	Jn	Jm	m^2		
J0 Photovoltaic Modules (NULL)	0	167	0	0	0		
J1Photovoltaic Modules 25% Roof	104.75	167	17493.25	17493.25	104.75		
J2 Photovoltaic Modules 50% Roof	200.95	167	33558.65	33558.65	200.95		
J3 Photovoltaic Modules 75% Roof	301.43	167	50338.81	50338.81	301.43		
	Equipment in number of units	Cost11 = $/unit	Km	Kn	W/m^2		
K0 Baseline Equipment	60	300	18000	0	20		
K1 Energy-Star Baseline	60	545.45	32727	14727	11		
K2 Energy-Star Top 10%	60	599.99	35999.4	17999.4	10		
K3 Energy-Star Top 5%	60	705.88	42352.8	24352.8	8.5		
	Lighting Area in m^2	Cost12 = $/m^2	Lm	Ln	W/m^2		
L0 Baseline Florescent Lighting	6028	115.62	696957.36	0	10		
L1 T-10 Florescent	6028	128.47	774417.16	77459.8	9		
L2 T-8 Florescent	6028	154.16	929276.48	232319.12	7.5		
L3 Compact Florescent	6028	212.94	1283602.32	586644.96	5.5		
L4 LED	6028	245.38	1479150.64	782193.28	1.2		
	Roof Area in m^2	Cost13 = $/m^2	Mm	Mn	U-Value (W/m^{2}K)	Absorption	Emissivity
M0 Baseline Roof, Metal Decking with Insulation	401.9	83.41	33522.479	0	0.2	0.6	0.4
M1 Metal Roof, Extruded Polystyrene (139.7mm)	401.9	99.53	40001.107	6478.628	0.14	0.6	0.4
M2 Metal Roof, Extruded Polystyrene (190.5mm)	401.9	116.12	46668.628	13146.149	0.12	0.3	0.7
	(Opaque) Wall Area in m^2	Cost14 = $/m^2	Nm	Nn	U-Value (W/m^{2}K)	Absorption	Emissivity
N0 Baseline Wall, EFIS	3537.7	75	265327.5	0	0.36	0.6	0.4
N1 Build Block ICF 4" 101.6mm + Acrylic Surfacing	3537.7	90.31	319489.687	54162.187	0.32	0.1	0.9
N2 Ray Core SIP 3.5" (88.9mm) + Acrylic Surfacing	3537.7	90.44	319949.588	54622.088	0.26	0.1	0.9
N3 Build Block ICF 6" + Acrylic Surfacing	3537.7	91.5	323699.55	58372.05	0.21	0.1	0.9
N4 Build Block ICF 8" + Acrylic Surfacing Systems	3537.7	92.68	327874.036	62546.536	0.16	0.1	0.9
N5 Ray Core SIP 5.5" (139.7mm) + Acrylic Surfacing	3537.7	106.56	376977.312	111649.812	0.14	0.1	0.9
N6 Ray Core SIP 7.5" (190.5mm) + Acrylic Surfacing	3537.7	115.42	408321.334	142993.834	0.11	0.1	0.9
	(Glazed) Window Area in m^2	Cost15 = $/m^2	Om	On	U-Value W/m2K	Emissivity	Transmittance
O0 Baseline Horizontal Double Glazing	1480.6	80.42	119069.852	0	2.1	0.7	0.5
O1 Double Air Low-E	1480.6	99.34	147082.804	28012.952	1.7	0.05	0.49
O2 Triple Air Low-E	1480.6	102.38	151583.828	32513.976	1.53	0.05	0.45
O3 SouthWall Super Glass QUAD Clear/Air/41mm	1480.6	186.15	275613.69	156543.838	0.84	0.05	0.42
O4 SouthWall Super Glass QUAD Clear/Argon/41mm	1480.6	187.22	277197.932	158128.08	0.65	0.05	0.4
O5 SouthWall Super Glass QUAD Clear/Argon/51mm	1480.6	191.53	283579.318	164509.466	0.55	0.05	0.4
O6 SouthWall Super Glass QUAD Clear/Krypton/51mm	1480.6	288.37	426960.622	307890.77	0.45	0.05	0.39
	Roof Area in m^2	Cost16 = $/m^2	Pm	Pn	m^2		
P1 Solar Boiler (NULL)	0	0	0	0	0		
P2 Solar Boiler 25% of Roof	104.75	21	2199.75	2199.75	104.75		

Figure A.6: Apartment Parametric Data

OFFICE PARAMETRIC DATA Figure.6			Cost (USD)	Premium Cost	(0<= factor= <1)		
	Lighting Daylighting Sensor (Area in m^2)	Cost1 = \$/m^2	An	Am			
A0 Baseline Daylight Sensor (NULL)	8467	0	0	0	1		
A1 Partial Daylight Sensor	8467	27.25	230725.75	230725.75	0.5		
A2 Fully Automated Daylight Sensor	8467	34.48	291942.16	291942.16	0.9		
	Lighting Occupancy Sensor (Area in m^2)	Cost2 = \$/m^2	Bn	Bm	(0<= factor= <1)		
B0 Baseline Occupancy Sensor (NULL)	8467	0	0	0	1		
B1 Partial OccupancySensor	8467	27.25	230725.75	230725.75	0.5		
B2 Fully Automated Occupancy Sensor	8467	34.48	291942.16	291942.16	0.9		
	Lighting Dimmer Control (Area in m^2)	Cost3 = \$/m^2	Cn	Cm	(0<= factor= <1)		
C0 Baseline Dimmer Switch (NULL)	8467	0	0	0	1		
C1 Partial Dimmer Switch	8467	11.03	93391.01	93391.01	0.5		
C2 Full Dimmer Switch	8467	16.54	140044.18	140044.18	0.9		
	Conditioned Area in m^2	Cost4 = \$/m^2	Dn	Dm	Heating COP	Cooling COP	
D0 Two-Pipe FCU, Standard Boiler and Chiller	8467	337.41	2856850.47	0	0.75	2.8	
D1 Two-Pipe FCU, Improved Boiler	8467	384	3251328	394477.53	0.85	3.2	
D2 Two-Pipe FCU, Air Source Heat Pump	8467	435.88	3690595.96	833745.49	1	3.5	
D3 Two-Pipe FCU, Ground Source Heat Pump	8467	784	6638128	3781277.53	3.4	4.25	
	Conditioned Area in m^2	Cost5 = \$/m^2	En	Em	Efficiency Rating		
E0 Baseline Heat Recovery (NULL)	8467	0	0	0	0		
E1 Loading Cold with Air-Conditioning	8467	51.9	439437.3	439437.3	40%		
E2 Two-Elements-System	8467	77.85	659155.95	659155.95	60%		
E3 Heat Exchange Plates or Pipes	8467	84.34	714106.78	714106.78	65%		
E4 Slowly Rotating or Intermittent Heat Exchangers	8467	90.83	769057.61	769057.61	70%		
	Conditioned Area in m^2	Cost6 = \$/m^2	Fn	Fm	Efficiency Rating		
F0 Exhaust Air Recirculation (NULL)	8467	0	0	0	0		
F1 Exhaust Air Recirculation (20%)	8467	2.9	24554.3	24554.3	20%		
F2 Exhaust Air Recirculation (40%)	8467	5.8	49108.6	49108.6	40%		
F3 Exhaust Air Recirculation (60%)	8467	8.7	73662.9	73662.9	60%		
	Envelope Area in m^2	Cost7 = \$/m^2	Gn	Gm	m^3/h/m^2		
G0 Baseline Air Tightness - Medium (Q4Pa 1.1 m3/h/m2)	6473.3	1.5	9709.95	0	1.2		
G1 Baseline Air Tightness - Low (Q4Pa 0.6 m3/h/m2)	6473.3	3.34	21620.822	11910.872	0.6		
	Conditioned Area in m^2	Cost8 = \$/m^2	Hn	Hm	Efficiency Rating		
H0 Baseline Stanfard Boiler	8467	32.53	275431.51	0	61%		
H1 Electric Boiler	8467	40	338680	63248.49	75%		
H2 Co-Generation Boiler	8467	48	406416	130984.49	90%		
	Conditioned Area in m^2	Cost9 = \$/m^2	In	Im	BEMS Class Rating		
I0 Building Energy Management System (NULL)	8467	0	0	0	1		
I1 User Adaptive BEMS	8467	50	423350	423350	2		
I2 Controller Optimized BEMS	8467	75	635025	635025	3		
I3 Fault Detection Diagnosis BEMS	8467	100	846700	846700	4		
	Roof Area m^2	Cost10 = \$/m^2	Jn	Jm	m^2		
J0 Photovoltaic Modules (NULL)	0	167	0	0	0		
J1Photovoltaic Modules 25% Roof	211.68	167	35350.56	35350.56	211.68		
J2 Photovoltaic Modules 50% Roof	423.45	167	70716.15	70716.15	423.45		
J3 Photovoltaic Modules 75% Roof	635	167	106045	106045	635		
	Equipment in number of units	Cost11 = \$/units	Km	Kn	W/m^2		
K0 Baseline Equipment	100	300	30000	0	20		
K1 Energy-Star Baseline	100	545.45	54545	24545	11		
K2 Energy-Star Top 10%	100	599.99	59999	29999	10		
K3 Energy-Star Top 5%	100	705.88	70588	40588	8.5		
	Lighting Area in m^2	Cost12 = \$/m^2	Lm	Ln	W/m^2		
L0 Baseline Florescent Lighting	8467	115.62	978954.54	0	10		
L1 T-10 Florescent	8467	128.47	1087755.49	108800.95	9		
L2 T-8 Florescent	8467	154.16	1305272.72	326318.18	7.5		
L3 Compact Florescent	8467	212.94	1802962.98	824008.44	5.5		
L4 LED	8467	245.38	2077632.46	1098677.92	1.2		
	Roof Area in m^2	Cost13 = \$/m^2	Mm	Mn	U-Value (W/m^{2}K)	Absorption	Emissivity
M0 Baseline Roof, Metal Decking with Insulation	846.7	83.41	70623.247	0	0.2	0.6	0.4
M1 Metal Roof, Extruded Polystyrene (139.7mm)	846.7	99.53	84272.051	13648.804	0.14	0.6	0.4
M2 Metal Roof, Extruded Polystyrene (190.5mm)	846.7	116.12	98318.804	27695.557	0.12	0.3	0.7
	(Opaque) Wall Area in m^2	Cost14 = \$/m^2	Nm	Nn	U-Value (W/m^{2}K)	Absorption	Emissivity
N0 Baseline Wall, EFIS	3186.5	75	238987.5	0	0.36	0.6	0.4
N1 Build Block ICF 4" 101.6mm + Acrylic Surfacing	3186.5	90.31	287772.815	48785.315	0.32	0.1	0.9
N2 Ray Core SIP 3.5" (88.9mm) + Acrylic Surfacing	3186.5	90.44	288187.06	49199.56	0.26	0.1	0.9
N3 Build Block ICF 6" + Acrylic Surfacing	3186.5	91.5	291564.75	52577.25	0.21	0.1	0.9
N4 Build Block ICF 8" + Acrylic Surfacing Systems	3186.5	92.68	295324.82	56337.32	0.16	0.1	0.9
N5 Ray Core SIP 5.5" (139.7mm) + Acrylic Surfacing	3186.5	106.56	339553.44	100565.94	0.14	0.1	0.9
N6 Ray Core SIP 7.5" (190.5mm) + Acrylic Surfacing	3186.5	115.42	367785.83	128798.33	0.11	0.1	0.9
	(Glazed) Window Area in m^2	Cost15 = \$/m^2	Om	On	U-Value W/m2K	Emissivity	Transmittance
O0 Baseline Horizontal Double Glazing	2440.1	80.42	196232.842	0	2.1	0.7	0.5
O1 Double Air Low-E	2440.1	99.34	242399.534	46166.692	1.7	0.05	0.49
O2 Triple Air Low-E	2440.1	102.38	249817.438	53584.596	1.53	0.05	0.45
O3 SouthWall Super Glass QUAD Clear/Air/41mm	2440.1	186.15	454224.615	257991.773	0.84	0.05	0.42
O4 SouthWall Super Glass QUAD Clear/Argon/41mm	2440.1	187.22	456835.522	260602.68	0.65	0.05	0.4
O5 SouthWall Super Glass QUAD Clear/Argon/51mm	2440.1	191.53	467352.353	271119.511	0.55	0.05	0.4
O6 SouthWall Super Glass QUAD Clear/Krypton/51mm	2440.1	288.37	703651.637	507418.795	0.45	0.05	0.39
	Roof Area in m^2	Cost16 = \$/m^2	Pm	Pn	m^2		
P1 Solar Boiler (NULL)	0	0	0	0	0		
P2 Solar Boiler 25% of Roof	211.68	21	4445.28	4445.28	211.68		

Figure A.7: Office Parametric Data

	Baseline Building	ASHRAE	Passivhaus	30% Optimization APT.	30% Cost Ranking APT.	30% Optimization Office	30% Cost Ranking Office	50% Optimization APT.	50% Cost Ranking APT.	50% Optimization Office	50% Cost Ranking Office
A0 (NULL) Daylight Sensor	■		■	■		■	■	■		■	■
A1 Partial Daylight Sensor		■									
A2 Fully Automated Daylight Sensor					■				■		
B0 (NULL) Occupancy Sensor	■		■	■		■	■			■	■
B1 Partial OccupancySensor		■						■			
B2 Fully Automated Occupancy Sensor					■				■		
C0 (NULL) Baseline Dimmer Switch	■	■		■		■	■				
C1 Partial Dimmer Switch								■	■	■	■
C2 Full Dimmer Switch					■						
D0 Two-Pipe FCU, Standard Boiler and Chiller	■		■	■	■	■	■	■	■	■	■
D1 Two-Pipe FCU, Improved Boiler		■									
D2 Two-Pipe FCU, Air Source Heat Pump											
D3 Two-Pipe FCU, Ground Source Heat Pump											
E0 (NULL) Heat Recovery	■			■	■	■	■			■	■
E1 Loading Cold with Air-Conditioning											
E2 Two-Elements-System											
E3 Heat Exchange Plates or Pipes											
E4 Slowly Rotating Heat Exchangers		■	■					■	■		
F0 Exhaust Air Recirculation (NULL)	■	■	■	■		■		■			
F1 Exhaust Air Recirculation (20%)					■		■			■	
F2 Exhaust Air Recirculation (40%)											
F3 Exhaust Air Recirculation (60%)									■		■
G0 Baseline Air Tightness - Medium	■										
G1 Baseline Air Tightness - Low		■	■	■	■	■	■	■	■	■	■
H0 Baseline Standard Boiler	■		■	■	■	■	■	■	■	■	
H1 Electric Boiler											■
H2 Co-Generation Boiler		■									
I0 (NULL) Building Energy Management System	■	■	■	■	■	■	■	■	■	■	■
I1 User Adaptive BEMS											
I2 Controller Optimized BEMS											
I3 Fault Detection Diagnosis BEMS											
J0 (NULL) Photovoltaic Modules	■	■	■	■		■				■	
J1Photovoltaic Modules 25% Roof					■		■	■			
J2 Photovoltaic Modules 50% Roof											
J3 Photovoltaic Modules 75% Roof									■		■
K0 Baseline Equipment	■		■								
K1 Energy-Star Baseline		■						■			
K2 Energy-Star Top 10%						■					
K3 Energy-Star Top 5%				■	■		■		■	■	■
L0 Code Compliant Florescent Lighting	■		■	■	■	■	■			■	
L1 T-10 Florescent								■	■		■
L2 T-8 Florescent		■									
L3 Compact Florescent											
L4 LED											
M0 Metal Decking with Insulation	■			■		■		■			
M1 Metal Roof, Extruded Polystyrene (139.7mm)		■	■							■	
M2 Metal Roof, Extruded Polystyrene (190.5mm)					■		■		■		■
N0 EFIS Wall	■			■	■	■	■				
N1 Build Block ICF 4" 101.6mm + Acrylic Surfacing											
N2 Ray Core SIP 3.5" (88.9mm) + Acrylic Surfacing		■									
N3 Build Block ICF 6" + Acrylic Surfacing											
N4 Build Block ICF 8" + Acrylic Surfacing Systems										■	
N5 Ray Core SIP 5.5" (139.7mm) + Acrylic Surfacing			■						■		■
N6 Ray Core SIP 7.5" (190.5mm) + Acrylic Surfacing								■			
O0 Double Glazing	■	■									
O1 Double Air Low-E				■	■		■				
O2 Triple Air Low-E						■		■	■		■
O3 SouthWall Super Glass QUAD Clear/Air/41mm			■							■	
O4 SouthWall Super Glass QUAD Clear/Argon/41mm											
O5 SouthWall Super Glass QUAD Clear/Argon/51mm											
O6 SouthWall Super Glass QUAD Clear/Krypton/51mm											
P0 (NULL) Solar Boiler	■	■	■			■				■	
P1 Solar Boiler 25% of Roof				■	■		■	■	■		■

Figure A.8: Selected Technology Comparison

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